VESIENTUTKIMUSLAITOKSEN JULKAISUJA
PUBLICATIONS OF THE WATER RESEARCH INSTITUTE 51

PERTTI SEUNA

SMALL BASINS — A TOOL IN SCIENTIFIC AND OPERATIONAL HYDROLOGY

Tiivistelmä

Pienet valuma-alueet tieteellisen ja sovelletun hydrologian tutkimusvälineenä

VESIHALLITUS — NATIONAL BOARD OF WATERS, FINLAND
Helsinki 1983

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ISBN 951-46-6724-7
ISSN 0355-0982

Helsinki 1983, Valtion painatuskeskus

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128300651N—12

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SEUNA, P. 1983. Small basins – a tool in scientific and operational hydrology. Publications of the Water Research Institute, National Board of Waters, Finland, No. 51.

Research in small basins has been practised for half a century in Finland. Statistical characteristics of hydrological quantities for designing hydraulic engineering works have especially been needed. This paper discusses recent studies carried out at four levels of the utilization and the experiences gained. Frequency and regression analyses of various hydrological quantities were carried out, long-term and short-term hydrological effects of forestry drainage as well as those of sub-drainage were studied and infiltration experiments were made. The experiences obtained justify the conclusion that a network of small basins is a useful – and for certain purposes – an irreplaceable tool of practical importance, whose costs and benefits are in reasonable balance. From a scientific point of view a few basins in the network should serve as field laboratories, and be used for process studies at the scale of a basin. The relatively high costs of basin research emphasize need for multidisciplinary studies.

Index words: hydrology, small basins, frequency analysis, statistical characteristics, design models, forestry drainage, hydrological effects, sediment discharge, sub-drainage, infiltration.

1. INTRODUCTION

1.1 The role of drainage area

A hydrological basin is a basic element that has been used in hydrological research since the dawn of this science (Perrault 1674). From the point of view of the areal scale different classes in basin studies can be distinguished.

Macroscale studies can be discussed in connection with large basins ($A > 200$ km^2). Observational results from large basins are useful as such. They can directly be used for various purposes in water resources management, such as hydropower production, water supply, flood control etc. of the basin in question. Simulation technique is often applied to a specific watercourse in these cases. In Finland these studies date from the beginning of this century. Large floods in 1899 acted as an impetus.

The second class of basin studies, those involving small basins, also have a long tradition in Finland. By small basins usually natural basins with an area smaller than 100—200 square kilometres are meant. These studies may be defined as mesoscale studies. Small basins provide a natural framework for various types of research, which will be discussed in more detail later. Typical characteristics are more distinguishable in small basins and these characteristics can also be surveyed, indentified and controlled more easily than in large basins. The instrumentation and data collection for small basins are also cheaper than for large ones, if the same areal accuracy is required.

A remarkable advantage is provided by the geological conditions in Finland. Relatively thin soil layers lay on fairly impermeable bedrock, and surface and sub-surface water divides usually coincide. Water balance of a basin can in these circumstances be reliably determined.

Observational results of small basins are seldom values in themselves, but need proper processing and interpretation.

A hydrological simulation of an individual small basin using a mathematical model is not usually needed, also contrary for large basins. However, if a study of a land use change and its hydrological consequences is based on data of only one small basin, simulation should be used.

Studies performed on small plots could be called microscale studies. This kind of studies have been made for studying the effects of a change in the basin, such as a silvicultural or an agricultural treatment.

Plots of some hectares or less in size provide the advantage that the treatments and characteristics can be measured and controlled even more easily than for small basins. Harmful effects could, however, arise from the unnatural feature of such a plot and from the decisive effect of the precise determination of the water divide, which very often is an artificial one.

Still smaller in scale are usually lysimeter studies and process studies. Although no natural basins are involved, lysimeters could in a way be compared with basins. The components of water balance are calculated, as is often done for basin studies. Unfortunately lysimeters usually create circumstances so different from nature that the interpretation of the results is often difficult to make indisputably.

1.2 Various ways of employing small research basins

From the point of view of basin use, different levels can be separated. First, direct use of the results mostly apply to large basins, which is often not the case for small basins. A direct transposition of the observational results from a small basin to a large or ungaged basin was originally one of the primary aims of the so-called representative basins. About three thousand such basins were established all over the world during the International Hydrological Decade of Unesco in 1965 to 1974. For the most part the direct transposition of the observational results using a reference "method" has proved to be impractical and unreliable. This was stated e.g. in the conclusions of the round-table discussions held in the International Symposium on the Influence of Man on the Hydrological Regime with a Special Reference to Representative and Experimental Basins in Helsinki in 1980 (Body 1981). Hydrological regionalization has been introduced to improve the transposition of results, but probably no general regionalization is able to contain specific characteristics, which would cover the different hydrological quantities required. For example, a regionalization suitable for annual water yield of a basin is not necessarily suitable for peak flows or for low flows. Furthermore, an individual basin within a hydrological region may remarkably differ from the general classification of that region. What was said above, does not underestimate the value of small basins as ordinary reference basins, used in the same way as large basins. Of course, their representativity is more limited than that of larger ones.

Secondly, the concept of a representative basin may be understood in a more general way. A set of hydrological components and physiographic characteristics with a range wide enough can be produced by these basins to allow a derivation of their relationships to be used for estimating the respective quantities in ungaged basins. Equations based on regression analysis are often developed to present such relationships. Design models, as these relationships are often called, are especially needed for the design of hydraulic engineering works. From the models some information is obtained on the true effects of the physiographic factors. These effects may, however, be seriously obscured by the intercorrelations of the physiographic characteristics. For the identification of more indisputable influences caused by a change in a certain characteristic, other methods, such as a control basin method, are needed.

Control basin studies can be considered as the third level in the use of hydrological basins. In this method paired basins are kept in their natural state during a calibration period. Following calibration the experimental basin is altered in accordance with the purpose of the study, while the other basin, the control basin, is kept in the natural state throughout the study. Using regression equations between the basins, the hydrological changes caused by the treatment can be calculated, providing no other changes in the basins have happened. The most important advantage of this method is that the consequences can be quantitatively determined. The method also has, however, drawbacks. A long time is usually needed, before the results are available. A calibration period shorter than five years is in general not sufficient, if the method is applied in an ordinary way. Difficulties may arise from undesired changes, which hardly can be avoided completely, when the research area is privately owned. Because more than one treatment can not be studied simultaneously, costly arrangements are needed, if the influences of several treatments are to be studied with this method. For this reason as many effects as possible should be studied in each control basin study. This also applies to basin studies in general; interdisciplinary research combining ecological, biological, water quality etc. studies should be incorporated in this framework.

The fourth level of basin use is formed by the research of hydrological processes. The study of these processes and the relationships between them at the scale of a basin was stated to be of primary importance in the conclusions of the aforementioned Helsinki Symposium. Physically-based models are held as the most promising means in this respect. However, so far no generally acceptable solution for relating model parameters to physiographic characteristics has been presented (Body 1981).

1.3 Purpose of this study

The main objective of small basin studies in Finland has been to produce information on hydrological quantities for the various design needs of hydraulic engineering works and water resources planning. In this respect both statistical characteristics and the factors influencing them have been important. This objective has been significant, and still is, since the first plans of the networks although different aspects have been stressed during the half century of the studies.

Land use changes are rather slight in Finland, in general. An exception, however, is the drainage of peatlands for forestry. This treatment has been carried out on a large scale since the beginning of the 1960's. By the end of the 1970's about 5.5 million hectares were drained — an area representing one fifth of Finland's land area. As early as in the 1930's forestry drainage was considered to be an activity, which could have considerable hydrological consequences. For this reason it was included in the studies of small basins almost from the very beginning. Forestry drainage is important from the economic point of view, since the role of forest industry has traditionally been superior in the Finnish economic life.

A changeover of cultivated lands from open-ditched to sub-drained had reached 800 000 ha or 32 per cent of Finland's total cultivated area by the end of the 1970's. According to the comprehensive SARA-program (1980), the sub-drained area is estimated to grow by 1 000 000 ha, i.e. to 70 per cent, by the end of this century. The possible consequences, not studied much up till now, are most effectively concentrated in southern and western Finland, where minimum runoffs are low and the watercourses thus sensitive to pollution. In these areas also other sources of pollution are numerous.

In Finland a network of small basins was started in the early 1930's. In its present arrangement, after a complete renewal, it has been in operation for more than twenty years. In the set of studies an opportunity was taken to use this tool in the different levels described earlier.

Observational data from 37 basins, which have the data series of not less than 10 years, have been analysed (Seuna 1982 c). Statistical characteristics of various runoff quantities are presented, based on frequency analyses of mean annual, spring, spring maximum, summer maximum, 30-day winter minimum and 30-day summer minimum runoffs.

Influence of physiographic characteristics on maximum runoffs and on their ratios are studied using a multivariate regression analysis (Seuna 1983 a). Models based on readily available characteristics are presented for the practical design of hydraulic engineering works.

The concept of an experimental basin is next discussed. Long-term and short-term effects of forestry drainage on runoff and sediment discharge have been analysed. In this connection changes in annual, monthly, spring and summer maximum, winter and summer minimum runoffs in the Huhtisuo basin, in south-eastern Finland (long-term) (Seuna 1982 a), and in the Ylijoki basin, in northern Finland (short-term) (Seuna 1982 b) are discussed. Changes in sediment transport in the Ylijoki basin are also dealt with, which has not been studied in Finland up till now.

The effects on water quantity caused by sub-drainage in a cultivated area have been studied in an experimental basin at Vihti, in southern Finland (Seuna and Kauppi 1980, 1982).

As a separate micro-scale investigation infiltration and its dependence on some physiographic characteristics has been carried out in the Kylmänoja basin at Vihti (Seuna 1983 b). In this study, field measurements using a modified double-ring infiltrometer have been carried out during eight summers.

In the following, results and experience obtained from these studies, and possibilities to develop the further use of these basins, are discussed.

2. HISTORICAL REVIEW

2.1 Finland

Research in small hydrological basins in Finland can be considered to have started at the beginning of the 1930's. In 1929 a network of 32 basins were initiated by the National Board of Agriculture at the instigation of Dr. Pekka Kokkonen (Kaitera 1936). Hydrological information for agricultural hydraulic activities was badly needed and the basin research of this network was also mentioned in the research programs as an investigation area of high priority. The drainage area of the basins originally varied from 12 to 700 km^2, but was soon reduced, mainly on the initiative made by Kaitera. Five of the river basins (> 200 km^2) were transferred to the network of the Hydrographical Bureau and three were terminated. At the same time new basins were established in such a way that the variation of drainage area was from 4 to 200 km^2 after the rearrangement (Kaitera 1936). Another principle and aim in rearranging the network was the grouping of several nearby basins of variable size and lake percentage, natural conditions with variation in soil, topography, vegetational cover and state of cultivation. The discharge conditions had to be undisturbed and natural. Especially backwater effect from downstream had to be avoided. In part of the basins measuring weirs were planned. Precipitation, snow and frost observations had to be available from all basins. The road connections had to be taken into account in such a way that measurements and maintenance could be easily carried out from the agricultural engineering districts. In the end of 1935 there were 50 basins, ten of which were equipped with measuring weirs.

On the basis of maps and field surveys the water divide, soil type and its permeability, vegetational cover, the state of cultivation, and the altitude of each basin were defined. Rating curves were determined, based mainly on field measurements employing current meters and on measuring weirs utilizing theoretical computations also.

Results from these studies have been published by Kaitera (1936, 1939, 1949), Niinivaara (1953) and Wäre (1951, 1957).

Towards the end of the 1950's an increasing need for a rearrangement of the network became evident due to the accelerated development in hydraulic engineering. The design of water supply and sewerage systems, in addition to water pollution control and river regulation needed far more accurate observations than those carried out under the old system, especially as far as low flow and mean runoff were concerned. It became clear that the changes in the natural channel due to plant growth, erosion, silting and freezing in winter time caused such changes in rating curves that sufficient accuracy could not be achieved using natural control. Thus the use of artificially fixed control sections, i.e. measuring weirs, were considered necessary in all basins.

As early as the latter part of the 1940's, three small basins, 7 to 24 hectares in area, were started at Vihti by Wäre (Wäre 1957, Mustonen 1963a) and from 1957 to 1962 a profound re-establishment of the network was realized (Mustonen 1965 b). Only four basins from the old network could be included in the new system, due to lakes, the slope in the channel required by the weir, or other requirements. An important criterion in selecting basins was the absence of lakes, as information on actual inflow was needed. It is well-known that lakes cut runoff peaks by storing flood waters. They also increase evaporation of the basin in most cases.

The physiographic characteristics of the basins were studied using maps and point line surveys, utilizing 100—200 points per basin. At each investigation point terrain type and soil type were determined by eye. Growing stock and coverage of forest and the land slope were measured and soil samples at a depth of 30 cm were taken at the same points. When categorizing terrain types, cultivated land, building sites, roads, forests on firm land, spruce swamps, pine bogs, open bogs and ponds were distinguished. The volume of growing stock and the distribution of the species of trees were defined. As far as the drainage network was concerned, the main channels were levelled and the state of drainage in cultivated land was studied. The total area surveyed was about 650 km^2, and 480 km of water channels were levelled. The number of investigation points amounted to around 5 500; e.g. more than ten tons of soil samples were analysed in the laboratory. Seven summer periods of one investigator were needed to complete these surveys.

Field surveys were repeated from 1974 to 1977 in order to measure the changeable parameters, such as volume of growing stock and drainage networks.

In recent years a few new basins have been established so that the network at the end of 1982 amounted to 58 basins. This figure includes a comprehensive control basin study, the so-called Nurmes-research, in which the effects of silvicultural treatments on water quantity and quality will be studied.

During the International Hydrological Decade (1965—1974) one basin study, that of Lake Pääjärvi, was started with the primary aim of studying lake evaporation. The biggest part of this study was completed by the end of the 1970's.

Numerous investigations based on these basins have been presented. They have been mostly concerned with the hydrological aspects (Wäre 1961 a, Mustonen 1963 a, b, 1964, 1965 a, b, c, d, 1967 a, b, 1968 a, b, 1971, Mustonen and Laikari 1961, Mustonen and Seuna 1969 a, b, 1970, 1971 a, b, 1972, 1973, 1980, Kuusisto 1973, Seuna 1971 a, b, 1972, 1974, 1977 a, b, 1978 a, b, 1980, 1982 a, b, c, 1983 a, b).

Some of the studies have also dealt with questions related to water quality (Wäre 1961 b, Kauppi 1979 a, b, c, Seuna and Kauppi 1980, 1982).

In Fig. 1, 39 of the present small basins, used for this set of studies, are shown. Thirty seven basins were used for frequency and regression analyses, the two others (119 and 120) were employed for a control basin study of forestry drainage. Figure 2 introduces a measuring weir, typical for these basins.

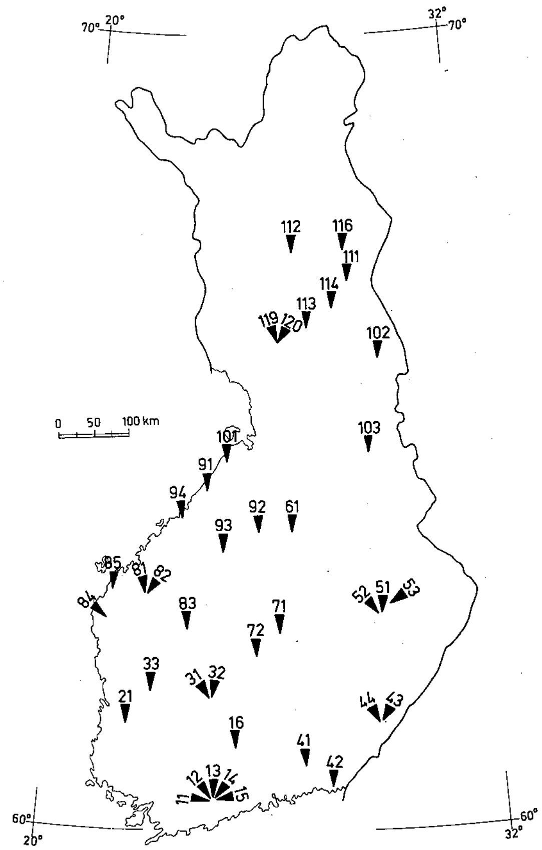

Fig. 1. A network of thirty seven small basins used in the statistical analyses of this study. In addition are shown the Ylijoki (119) and the Kotioja (120) basins, which are used only for the studies dealing with the short-term effects of forestry draining (chapter 5).

2.2 Other countries

In the other Nordic countries basin research has been slightly different from Finland's. In Sweden a somewhat similar system has been developed in recent years. Under these plans interdisciplinary research objectives were incorporated. Norway has developed separate networks for agricultural studies, urban hydrology and glacier studies and they have been operating since the 1960's. On the main each of the networks comprises some 20 basins. In Denmark basin studies have concentrated heavily on ground water and agriculture, which is natural when considering the Danish environment. In 1977 a comprehensive multidisciplinary study, the Suså project was started.

Basin studies were strongly stimulated by the launch of the Unesco International Hydrological Decade (1965—1974). In the Nordic countries 15 well-instrumented basins were established, seven of them in Sweden, three in Norway, three in Denmark of which one in Greenland, one in Iceland and one in Finland (Falkenmark 1972). The objectives of those basin studies were rather ambitious (Nordiska arbetsgruppen för representativa områden 1975):

- to study hydrological processes,
- to quantify different components of the hydrological cycle within the basins,
- to describe the hydrological regime,
- to develop and test new instruments and methods,
- to use the basins as a basis for extrapolation and for hydrological maps,
- to use the results for principal investigations in different fields of research by utilizing the dense networks of the basins,
- hydrological training.

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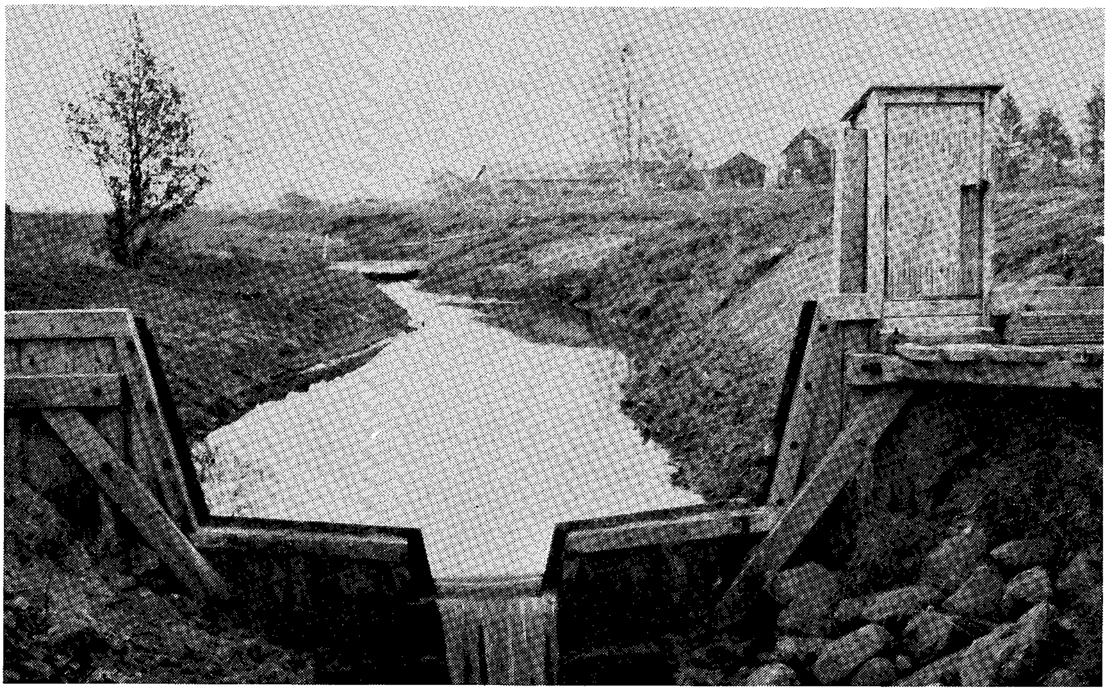

Fig. 2. The measuring weir of the Tuuraoja basin (No 91, Fig. 1).

In Sweden the main objectives of the IHD-basins were the development of pre-urban and urban runoff models (Värpinge), the water holding capacities of peatlands (Komosse), lake hydrology and actual evaporation over forest (Velen), ground water chemistry (Verkaån), snow studies and water balance of peatlands (Lappträsket), glacier studies (Tarfala) and water budget and hydrological processes in general (Kassjöån).

In Norway the IHD-basins represented a fjeld area (Filefjell), a ground water area (Romerike) and a steeply sloping forest area (Sagelva).

In Denmark the Stevns-basin was established for the measurement of actual evaporation and the Karup basin to study soil moisture storage in deep soils and also actual evaporation. Additionally there was the Narssaq basin in Greenland for glacier studies, for ground water observations and for hydrochemical studies.

In Iceland the Ellidaar-basin was meant for the study of water budget and hydrological processes.

Many of the Nordic IHD-basins have been closed up till now.

In the light of the experiences obtained, the results did not quite correspond to their high cost. This has been stated after the IHD-period in several connections e.g. by common concensus in the critical discussions in the international symposia of Helsinki in 1980 and of Bern in 1982 (Body 1981, 1982, Mc Culloch 1982).

In the late 1960's a strong belief in the sophisticated mathematical methods gained ground. In this context generated data were considered to enable to substitute actual observations, for a notable part. Towards the end of the 1970's more practical and realistic aspects have been underlined, due to e.g. the maximisation of practical benefit from the financial investments.

3. FREQUENCY ANALYSES OF RUNOFF QUANTITIES

Statistical characteristics of runoff quantities are needed for various design problems of hydraulic engineering works and water resources planning. On the basis of the observations from 37 basins, shown in Fig. 1 and Table 1, frequency analyses were carried out for mean annual, spring, spring and summer maximum, winter and summer

Table 1. Data on basin characteristics at the end of the observation period 1958—1977.

Drainage basin	Area km^2	Cultivated land %	Peat land %	Forest on firm land %	Tree stand m^{3}ha^{-1}	Mean slope %	Max altitude m a.s.l.
11. Hovi	0.12	100	0	0	0	2.8	56
12. Ali-Knuutila	0.24	48	0	42	55	10.0	90
13. Yli-Knuutila	0.07	0	0	100	162	16.0	92
14. Teeressuonoja	0.69	0	13	87	116	13.9	111
15. Kylmänoja	4.04	27	11	60	52	8.2	115
16. Koiranoja	6.21	26	11	58	73	7.0	177
21. Löytäneenoja	5.64	77	1	20	19	1.7	53
31. Paunulanpuro	1.50 1)	2	18	77	82	6.8	147
32. Siukolanpuro	1.86 2)	9	16	74	48	7.5	147
33. Katajaluoma	11.2	3	43	54	45	2.9	165
41. Niittyjoki	29.7	35	2	59	45	4.9	107
42. Ravijoki	56.9	17	25	56	50	6.4	63
43. Latosuonoja	5.34	19	15	66	74	8.2	131
44. Huhtisuonoja	5.03	0	44	56	39	5.0	132
51. Kesselinpuro	21.7	4	39	54	88	4.2	149
52. Kuokkalanoja	2.76	21	14	62	72	5.8	145
53. Mustapuro	11.2	15	34	51	60	3.2	123
61. Korpijoki	122	8	65	27	44	3.1	200
71. Ruunapuro	5.39	22	10	67	66	6.4	176
72. Heinäjoki	9.40	8	10	81	76	7.6	218
81. Haapajyrä	6.09	58	15	26	23	3.0	47
82. Kainastonluoma	79.2	27	20	51	53	3.8	63
83. Kaidesluoma	45.5	13	26	59	46	3.3	178
84. Norrskogsdiket	11.6	34	30	36	48	1.6	41
85. Sulvanjoki	26.8	23	11	65	67	3.6	46
91. Tuuraoja	23.5	16	47	40	27	2.0	55
92. Tujuoja	20.6	12	40	43	46	2.3	152
93. Pahkaoja	23.3	2	53	43	40	2.1	202
94. Kuikkisenoja	8.05	31	22	47	62	3.9	28
101. Huopakinoja	19.7	17	26	56	53	2.6	76
102. Vääräjoki	19.3	0	34	64	30	5.0	354
103. Myllypuro	9.86	2	27	70	59	7.4	259
111. Kuusivaaranpuro	27.6	2	26	71	30	5.2	324
112. Lismanoja	2.77	2	37	57	16	7.8	350
113. Korintteenoja	6.13	2	5	92	37	10.2	352
114. Vähä-Askanjoki	16.4	0	17	83	14	10.9	383
116. Myllyoja	28.5	1	12	87	40	7.4	411
Mean	18.27	18.5	22.1	57.9	52.9	5.8	159.9
Standard deviation	24.27	22.4	16.1	20.8	29.3	3.4	106.0

1) before 3/1968 A = 3.01 km^2, 2) before 3/1968 A = 3.37 km^2

minimum runoffs (Seuna 1982 a). In the data set, which was available, the longest series covered a period of 20 years. Series shorter than 10 years were not included. The period of 20 years may be considered long enough to allow a preliminary, statistical analysis. One should notice, however, that the longer the period, the more probably changes have occurred in the properties of such basins.

In the analysis the straight lines of frequency were fitted by eye, even if this method introduces a subjective trait. The computational method was not used mainly due to the fact that the outliers would have received too much stress with a series so short. This would have lead to erroneous results. The effect of exceptional cases on hydrological frequency analyses was shown e.g. by Linsley, Kohler and Paulhus (1958).

In the frequency analysis the distribution chosen for the annual runoff and the spring runoff was the normal (Gaussian) distribution, for the maximum runoff the Gumbel distribution of extreme values and for the minimum runoff the Weibull distribution (the Gumbel distribution with a logarithmic scale on runoff axis). These distributions were chosen on the basis of try-out and previous experience. So the normal distribution was tried on e.g. the maximum runoff and the log-normal distribution on the annual runoff and for certain basins the fit was good. It is not justified, however, to use different distributions for the same runoff quantity in various basins for a short period of observations, even if this would lead to a better fit. Therefore, the same distribution was chosen for all basins for a given runoff quantity even if the points did not always group themselves in a linear manner. The thirty-day minimum runoff and the annual runoff points especially grouped themselves for a few basins with a clear angle. In these cases two intersecting straight lines, "a dog-leg", were drawn by eye to fit the points. This is justified, if the points may be considered to belong to two different populations. This is certainly the case with the thirty-day minimum runoff, which in part stems from ground water but is also partly derived from rain water or from the melting of snow.

In the same manner the annual runoff in many basins clearly contains an appreciable portion of groundwater outflow, which determines a minimum for the annual runoff. This is especially the case for the smallest basins and for the basins with an abundance of coarse soils. Therefore in such cases two intersecting straight lines were also drawn for the recurrence. Two straight lines might have been connected by a curve, thus having a better fit round the intersection area. This area is, however, of little practical interest in regard to the recurrence. For this reason, and considering the shortness of the observation period, a curved connection was not used. The utilization of full curves cannot be regarded justified theoretically. The method of two straight lines has been commented on and used by e.g. Lyshede (1955), Potter (1958) and Potter, Stovicek and Woo (1968). Potter (1958) claims that rather small (less than 1000 km^2) catchments show recurrences of maximum flow, which may best be represented on Gumbel paper by two straight lines, which intersect at a return period of about 5 to 10 years.

The extrapolation of recurrence intervals far beyond the length of the observation period always contains a large risk and one should not extrapolate from 20 years further than 30 years. It has been calculated, that a 50-year value determined by the Gumbel distribution method on the basis of 25 years of observations, with a 68 percent confidence limit for the recurrence time, places this between 12 and 220 years (Bell 1969). On the other hand, it has been stated that a maximum value measured in 20 years of observations will recur with a one percent probability on average, after 4.9 years, or not until after 1990 years (Linsley, Kohler and Paulhus 1958).

During the observation period notable changes have taken place in the characteristics of a few basins. The most decisive of these have been in basins 11 and 44. Basin 11, which originally consisted of open-ditched cultivated land, was subdrained in 1971. The period after this change is too short, however, to treat it separately in the frequency analysis. In basin 44 peatlands consisting of about 40 percent of the catchment were drained for forestry from 1958 to 1960. Investigations have shown (Mustonen and Seuna 1971 a, b, Seuna 1980, 1982 a) that the draining caused the largest changes during the first post-treatment years. Most clearly this showed in the minimum runoff and in the summer maximum runoff.

When judging the results one should keep in mind that the method of extrapolation has an influence on the result of extrapolation. In exceptional cases different methods of extrapolation may render results differing by as much as 50 percent. So for basin 12 the annual runoff for a dry year, having a probability of 5 per cent equals to 3 l s^{-1} km^{-2}, when the broken line method is used, while a single straight line gives 1.5 l s^{-1} km^{-2}.

Examples of some frequency analyses are shown in Figs. 3, 4 and 5.

A summary of the annual variation of some runoff quantities is given in Table 2. Results from the frequency analyses have been presented earlier (Seuna 1982 c) and a brief summary is shown in Table 3.

3.1 Annual runoff

The mean annual runoff for the whole period from 1958 to 1977 varied for the various basins between 4.14 l s^{-1} km^{-2} and 13.24 l s^{-1} km^{-2} with a mean value of 8.52 l s^{-1} km^{-2} (Tables 2 and 3). The highest value for a single year has been 21.99 l s^{-1} km^{-2} (in 1962 basin 42), while the lowest was 1.63 l s^{-1} km^{-2} (in 1976 basin 13).

The mean annual runoff with a return period of 20 years (5 or 95 per cent) was in the mean for all basins more than 13.46 l s^{-1} km^{-2} or less than 4.21 l s^{-1} km^{-2}. The largest annual runoff values were

Table 2. A summary of the annual variation of some runoff quantities in small basins. Numbers in brackets indicate the basin of the maximum or minimum c_v, respectively.

Quantity	Total range $l\ s^{-1}\ km^{-2}$		Coefficient of variation in annual series (c_v)		
	Maximum	Minimum	Maximum	Minimum	Mean of all basins
Mean annual runoff	21.99	1.63	0.45 (13)	0.17 (114)	0.32
Spring runoff (1.3.—31.5., q_w)[1)]	294	21	0.53 (13)	0.19 (71)	0.31
Spring maximum runoff	463	19	0.64 (81)	0.21 (113)	0.41
Instantaneous spring maximum runoff	1209	19	0.66 (81)	0.24 (113)	0.42
Summer maximum runoff	355	1	1.39 (44)	0.38 (114)	0.82
Instantaneous summer maximum runoff	1872	1	1.68 (11)	0.41 (101)	0.87
Thirty-day winter minimum runoff	8.31	0.00	1.88 (12)	0.20 (102)	0.82
Thirty-day summer minimum runoff	14.25	0.00	3.60 (12)	0.19 (14)	1.15

1) in mm

Table 3. Basin values of some runoff quantities based on the frequency analyses of small hydrological basins in 1958 to 1977. Numbers in brackets indicate the basin of the maximum or the minimum average, respectively.

Quantity	Basin averages ($l\ s^{-1}\ km^{-2}$)					Standard deviation of the basin means $l\ s^{-1}\ km^{-2}$
	Maximum		Minimum		Mean	
Mq	13.24	(114)	4.14	(13)	8.52	1.96
q_w[1)]	202	(113)	70	(13)	142	26
Hq_w	217	(11)	59	(14)	119	38
$Hq_{w\ inst}$	456	(11)	73	(82)	157	72
Hq_s	82	(11)	21	(94)	43	15
$Hq_{s\ inst}$	273	(12)	24	(94)	69	53
$Nq_{w\ 30}$	3.50	(14)	0.13	(11)	1.31	0.85
$Nq_{s\ 30}$	8.06	(116)	0.04	(11)	1.74	1.89
Mq 1/20 min	9.15	(114)	1.50	(13)	4.21	1.72
Mq 1/20 max	21.50	(42)	8.10	(13)	13.46	2.68
q_w1/20 min[1)]	122	(102)	18	(13)	67	25
q_w1/20 max[1)]	294	(103)	146	(13)	219	32
Hq_w 1/20	423	(11)	126	(82)	223	70
$Hq_{w\ inst}$ 1/20	996	(11)	151	(14)	299	149
Hq_s 1/20	319	(11)	49	(101)	119	53
$Hq_{s\ inst}$ 1/20	1360	(11)	57	(101)	234	263
$Nq_{w\ 30}$ 1/20	1.63	(116)	0.00	2)	0.38	0.48
$Nq_{s\ 30}$ 1/20	3.82	(116)	0.00	3)	0.45	0.81

1) in mm
2) 11, 12, 13, 21, 81
3) 11, 12, 21, 31, 81, 83, 84, 85

found in the upland areas of eastern and northern Finland, which generally, even in dry years, yielded more than 5 $l\ s^{-1}\ km^{-2}$. The annual runoff with a return period of 20 years for dry years was on average 49 per cent and for wet years 160 per cent of the mean value for the whole observational data.

The mean annual runoff had a high correlation especially with the water equivalent of snow (r = 0.72), the altitude (r = 0.64) and the mean annual temperature (r = −0.58) on the basis of a preliminary regression analysis.

3.2 Spring runoff

The spring runoff was defined as the sum of runoff between March 1 and May 31 for practical reasons. Only for northern Finland was recession runoff added from June as long as it exceeded 30 $l\ s^{-1}\ km^{-2}$, however, not longer than one week.

Spring runoff varied between 21 and 294 mm for the whole data with a mean value of 142 mm (Tables 2 and 3). The averages for the various basins varied between 70 and 202 mm. Once in 20 years the mean spring runoff of all basins was less

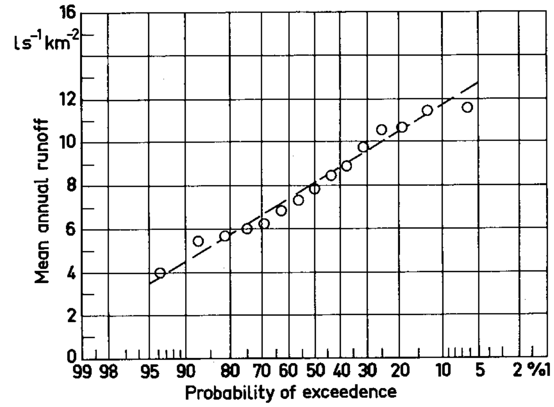

Fig. 3. An example of frequency analysis of mean annual runoff (Mq) for the basin 15, Fig. 1.

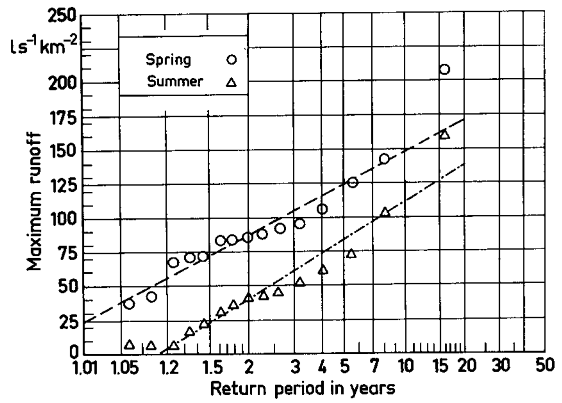

Fig. 4. An example of frequency analyses of spring and summer maximum runoffs (Hq_w and Hq_s) for the basin 15, Fig. 1.

than 67 mm with a variation over the basins from 18 to 122 mm (Table 3). Correspondingly, once in 20 years the mean spring runoff for all basins exceeded 219 mm with a variation over the basins from 146 to 294 mm.

3.3 Spring maximum runoff

For spring maximum runoff the largest daily value and the largest instantaneous runoff peak observed during the snowmelt period were taken.

The instantaneous peaks have belonged to the same peak as the maximum daily values. They fell

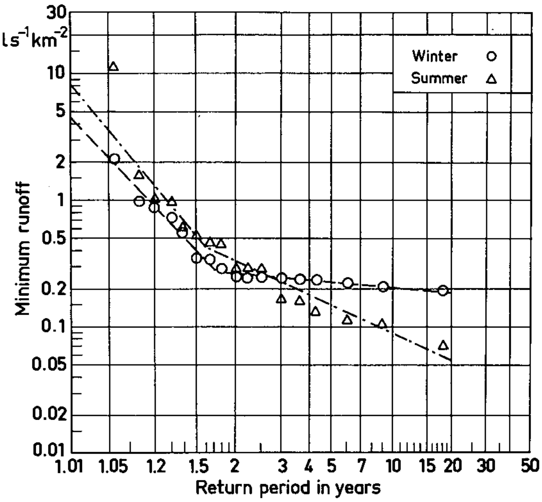

Fig. 5. An example of frequency analyses of winter and summer minimum runoffs (Nq_w and Nq_s) for the basin 92, Fig. 1.

almost always on the same dates as these.

The spring maximum runoff varied in the whole data from 19 to 463 l s^{-1} km^{-2} with a mean value of 119 l s^{-1} km^{-2} (Tables 2 and 3). The mean spring maxima for the separate basins varied between 59 and 217 l s^{-1} km^{-2}.

The spring maximum runoff from small basins occurred in 1958 to 1977 in the mean in southern Finland between 10th and 20th April and in northern Finland about one month later. The standard deviation of the dates occurred in southern Finland and in the vicinity of the coast 11 to 13 days, which is clearly more than in northern Finland, where it was only 7 days (Fig. 6).

The spring maximum runoff with a return period of 20 years varied from 126 to 423 l s^{-1} km^{-2} with a mean value of 223 l s^{-1} km^{-2}. The spring maximum runoff occurring once in 20 years for the individual basins was 1.50 to 2.44 times the mean spring maximum runoff, with a mean ratio of 1.91. This ratio was larger than that found in a previous study (Niinivaara 1961). The frequency analysis of the ten-year data from 1958 to 1967 of the same basins gave 1.90 for the mean ratio (Mustonen 1968 b). For some basins, however, the frequency analysis of 10 years gave Hq 1/20 values notably different from those obtained in the 20-year analysis.

The instantaneous spring maxima for all data varied from 19 to 1209 l s^{-1} km^{-2} with a mean of 157 l s^{-1} km^{-2}, while the basin averages were 73 to 456 l s^{-1} km^{-2}.

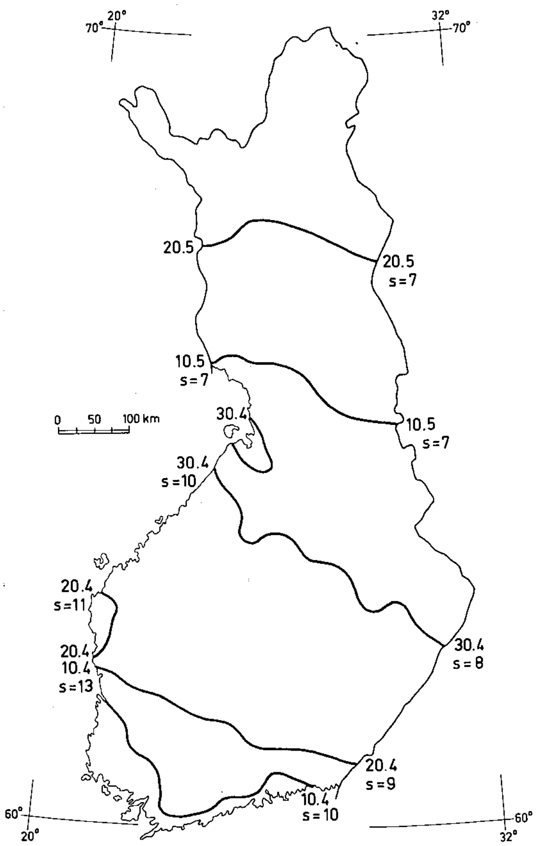

Fig. 6. The average occurrence date and the standard deviation of the date of spring maximum runoff in 1958 to 1977. Standard deviations indicate an average value for coastal or inland areas in concern, but do not refer to the isolines.

The instantaneous spring maximum runoff with return period of 20 years varied from 151 to 996 l s^{-1} km^{-2} with an average of 299 l s^{-1} km^{-2}. The ratio of 20-year value to the basin mean varied in the basins from 1.50 to 2.65 with an average of 1.91.

The instantaneous spring maximum runoff was 1.01 to 3.48 times the maximum daily spring runoff. The ratio $MHq_{w\ inst}/MHq_w$ for the various basins varied from 1.04 to 2.10 with a mean value of 1.31. The largest instantaneous maximum spring runoff for a single year, 1209 l s^{-1} km^{-2}, was measured in 1966 in the 12 ha Hovi basin (basin 11), consisting of cultivated land. The corresponding daily maximum runoff was 463 l s^{-1} km^{-2}. Spring maximum runoff and influencing factors are discussed in more detail in chapter 4.1.

3.4 Summer maximum runoff

The summer maximum runoff was defined as the largest daily runoff between 1 June and 31 October. During some years, especially in northern Finland, the recession runoff still continued in the first part of June. If the recession part of the runoff was appreciable this runoff was not accepted as summer runoff. In the southern and southwestern coastal areas, on the other hand, large runoff peaks caused by rain have occurred in May, but definitely after the end of the snowmelt. These runoff peaks were accepted as summer maxima.

The summer maximum runoff varied in the whole material between 1 and 355 l s^{-1} km^{-2} with a mean value of 43 l s^{-1} km^{-2} (Tables 2 and 3). The mean values for the basins varied between 21 and 82 l s^{-1} km^{-2}.

The summer maximum runoff with an average return period of 20 years, varied in the separate basins between 49 and 319 l s^{-1} km^{-2} with a mean value of 119 l s^{-1} km^{-2}. The summer maximum runoff, recurring once in 20 years, was in the individual basins 1.8 to 4.5 times the mean summer maximum runoff with a mean ratio of 2.74. The smallest basins and those containing a lot of cultivated land in this case also showed extreme properties.

The variation of the instantaneous maxima of the cases of daily maxima was from 1 to 1872 l s^{-1} km^{-2} with a mean of 69 l s^{-1} km^{-2}, while the basin averages varied from 24 to 273 l s^{-1} km^{-2}.

The instantaneous summer maximum runoff with return period of 20 years, varied from 57 to 1360 l s^{-1} km^{-2}. The ratio of a 20-year value to the basin mean varied in the basins from 1.97 to 5.98 with the average of 3.06. The ratio thus clearly exceeded that of spring maximum runoff.

The instantaneous summer maximum runoff was in the mean 1.6 times the respective daily maximum. The ratio $MHq_{s\ inst}/MHq_s$ varied between 1.04 and 3.59 for the separate basins and for a single year the instantaneous maximum summer runoff was more than five times the corresponding daily runoff. In the summer of 1968 the largest instantaneous summer maximum runoff, namely 1872 l s^{-1} km^{-2}, was measured in the Hovi basin which consisted of cultivated land. The corresponsing daily mean was 290 l s^{-1} km^{-2}.

The spring maximum runoff values, even on small drainage basins, are clearly greater than the summer maximum runoff values. In very small basins during exceptional years the summer maximum runoff may, however, rise to an appreciable height. For a small area containing a lot of cultivated land, the summer maximum runoff has a markedly more extreme distribution and the instantaneous summer maximum runoff still more so, than the corresponding distributions for the spring maximum runoff. In these cases the instantaneous summer maximum runoff may clearly exceed the corresponding spring maximum runoff and thus form an important base for water management planning. On land with covered drainage, however, the capacity of the tiles will in most cases limit the amplitude of the maximum.

The summer maximum runoff on average occurred at the end of August or in the beginning of September. However, the variation was extremely large; the average standard deviation of the date being 51 days. But the summer peaks, which may be attributed solely to rain still tend to occur towards the autumn.

The factors influencing summer maximum runoff are discussed in more detail in chapter 4.2.

3.5 Winter minimum runoff

The winter minimum runoff was computed as the smallest mean runoff of 30 consecutive days falling between the beginning of the year and the spring flood.

Basin averages for 30-day winter minimum runoff varied from 0.13 to 3.50 $l\ s^{-1}\ km^{-2}$ with an average of 1.31 $l\ s^{-1}\ km^{-2}$ (Tables 2 and 3). Winter minimum runoff with return period of 20 years varied in separate basins from 0 to 1.63 $l\ s^{-1}\ km^{-2}$ with an average of 0.38 $l\ s^{-1}\ km^{-2}$. The lowest values represent small basins containing a large portion of cultivated land, and they are often situated close to the coastal zone. The highest values come from the basins possessing a lot of coarse soils, as could be expected.

The winter minimum runoff began on average between 15 February and 15 March and the various basins did not differ much from one another. On the other hand, the data within a basin varied markedly in different years—standard deviation was about three weeks.

3.6 Summer minimum runoff

The summer minimum runoff was defined as the smallest mean runoff for a period of 30 consecutive days falling between the spring flood and 31 October.

Basin averages for 30-day summer minimum runoff varied from 0.04 to 8.06 $l\ s^{-1}\ km^{-2}$ with an average of 1.74 $l\ s^{-1}\ km^{-2}$ (Tables 2 and 3). Summer minimum runoff with return period of 20 years varied in separate basins from 0 to 3.82 $l\ s^{-1}\ km^{-2}$ with an average of 0.45 $l\ s^{-1}\ km^{-2}$. Naturally, summer minimum runoff had the lowest values on the smallest basins containing a large amount of cultivated land. Summer minima generally had rather high values in northern Finland.

The summer minimum runoff began, on average, on 21 July. The standard deviation of the date was 27 days. The minimum was reached earliest in the basins containing a large portion of cultivated land, in general in the areas on the southern and western coasts.

From the point of view of water supply and of irrigation especially, summer runoff and summer minimum runoff vs. time were determined for various levels of probability (Seuna 1977 b). As an example sixteen basins, half of them being small basins, were chosen. It was shown that for the use in concern it is important to relate low flow with the date of the summer, but not to consider the absolute values of low flow alone. The significance of the date and the duration of low flow has been also emphasized by e.g. Kajosaari (1968) and Mustonen (1971).

A satisfactory estimation of minimum runoff has turned out to be a very difficult task, if only simple regression models are used (Mustonen 1965 c, Seuna 1970). Using a more sophisticated method a better degree of determination was achieved (Mustonen 1971). Methods to estimate statistical characteristics of dry spells have been developed by Velner and Kask (1968).

Minimum runoff was not analysed in this study. As an example, only a preliminary regression analysis for the data of the 20-year period was carried out using the same set of independent variables as for the maximum runoff. The mean 30-day summer minimum $MNq_{s\ 30}$ ($l\ s^{-1}\ km^{-2}$) was explained satisfactorily, using the mean water equivalent of snow on the preceding 31 March (W_e) and the maximum difference in the altitude of a basin (E_d)

$$MNq_{s\ 30} = 0.022\ W_e + 0.015\ E_d - 1.95 \qquad (1)$$
$$R = 0.879$$
$$s_e = 0.93$$

The water equivalent of snow near to the end of winter also indicates many other characteristics, such as northern location, high altitudes, a small amount of cultivated land, a short summer etc.

The other quantities of the minimum runoff could not be explained on a satisfactory level in this context.

3.7 Discussion

In frequency analyses, two principles were followed. First, frequency lines were fitted by eye. An analytical fit was not applied, in order to avoid the effect of the outliers in rather short series of observations.

Secondly, straight lines or two intersecting lines were used instead of a curved fit. The use of intersecting lines was based partly on the shortness of the observations, but for the major part on the fact that two separate populations were included in certain series of observations.

From a practical point of view the choice of the fitting method is important, as it may have a considerable effect on the values obtained by extrapolation, in an exceptional case. Therefore, in such a case a special caution should be practised in extrapolation. The range of observation period should not be notably exceeded in an ordinary case, either.

4. REGRESSION ANALYSES OF MAXIMUM RUNOFF

Using a multivariate regression analysis, equations for spring and summer maximum runoffs were calculated (Seuna 1983 a). Only variables, which could be defined from maps or from readily available statistics were used. These were e.g. drainage area, percentage of cultivated land, altitude, volume of growing stock, etc. Some long-term averages of meteorological factors were also included and these can be regarded as basin factors as well. In the analysis 37 basins with observation series of ten or more years were included (n = 37).

The dependent variables are as follows

MHq_w = mean value of the spring maximum runoff
MHq_s = mean value of the summer maximum runoff
$MHq_{w\ inst}$ = mean value of the instantaneous spring maximum
$MHq_{s\ inst}$ = mean value of the instantaneous summer maximum
Hq_w 1/20 = spring maximum runoff with return period of 20 years
Hq_s 1/20 = summer maximum runoff with return period of 20 years
$Hq_{w\ inst}$ 1/20 = instantaneous spring maximum with return period of 20 years
$Hq_{s\ inst}$ 1/20 = instantaneous summer maximum with return period of 20 years

In addition to this, the ratios of $MHq_{w\ inst}$ and MHq_w; Hq_w 1/20 and MHq_w; $Hq_{w\ inst}$ 1/20 and Hq_w 1/20; $Hq_{w\ inst}$ 1/20 and MHq_w; and the respective ratios for summer maximum were explained using the same independent variables.

The mean values and the standard deviations of the independent variables are presented in Table 4 and a correlation matrix of the independent variables is shown in Table 5.

Table 4. The mean values and standard deviations of the independent variables (see the list of symbols).

Variable	Unit	Mean	Standard deviation
A	km^2	18.3	24.3
C	%	18.5	22.4
C_s	%	11.4	17.0
F	%	57.9	20.8
B	%	23.0	17.1
B_o	%	6.7	9.3
B_d	%	9.2	11.0
b_i	—	1.70	1.94
I_s	%	1.32	1.56
D_d	km^{-1}	1.54	0.95
F_s	m^3ha^{-1}	52.5	28.4
F_c	%	31.3	13.2
G_r	%	57.2	18.8
G_f	%	14.1	18.3
G_c	%	7.4	13.0
G_g	%	2.6	4.3
L_b	km	6.3	4.5
k_e	—	0.41	0.19
k_c	—	0.50	0.17
L_c	km	7.5	5.9
S_c	%	1.09	1.77
L_w	km	4.0	3.1
S_w	%	1.04	1.87
E_w	m	103	68
E_o	m	87	62
E_p	m	160	106
E_d	m	73	57
S_m	%	5.8	3.4
s_i	‰	11.2	17.0
t_w	h	1.22	0.96
T_a	°C	2.8	1.47
P_a	mm	653	60
P_s	mm	191	19
W_m	mm	113	24
W_h	mm	113	33
W_e	mm	116	40
W_p	mm	124	38

Table 5. Correlation matrix of the independent variables (see the list of symbols).

	A	C	C_s	F	B_o	I_s	B	B_d	b_i	D_d	F_s	F_c	G_r	G_f	G_c	G_g	L_b	k_e	k_c	L_c	S_c	L_w	S_w	E_w	E_o	E_p	E_d	S_m	s_i	t_w	T_a	P_a	W_m	P_s	W_h	W_e	W_p
A	1.00																																				
C	−0.14	1.00																																			
C_s	−0.08	0.64	1.00																																		
F	0.21	−0.74	−0.41	1.00																																	
B_o	0.02	−0.34	−0.23	−0.10	1.00																																
I_s	−0.18	0.19	−0.03	0.10	−0.27	1.00																															
B	0.44	−0.45	−0.35	−0.26	0.61	−0.45	1.00																														
B_d	0.11	−0.31	−0.22	−0.12	0.29	−0.36	0.61	1.00																													
b_i	0.16	−0.32	−0.22	−0.13	0.42	−0.40	0.63	0.88	1.00																												
D_d	−0.38	0.55	0.18	−0.27	−0.24	0.28	−0.44	−0.14	−0.19	1.00																											
F_s	−0.13	−0.37	−0.15	0.59	−0.37	0.23	−0.24	−0.06	−0.11	0.05	1.00																										
F_c	−0.01	−0.51	−0.22	0.61	−0.29	0.15	−0.09	0.07	−0.01	−0.11	0.83	1.00																									
G_r	−0.12	−0.57	−0.15	0.79	−0.06	−0.17	−0.23	−0.11	−0.05	−0.44	0.24	0.32	1.00																								
G_f	−0.18	0.87	0.53	−0.50	−0.41	0.43	−0.59	−0.39	−0.44	0.66	−0.09	−0.22	−0.60	1.00																							
G_c	−0.07	0.86	0.44	−0.59	−0.28	0.28	−0.45	−0.29	−0.33	0.57	−0.26	−0.34	−0.61	0.92	1.00																						
G_g	0.07	−0.03	−0.18	0.06	0.03	0.42	−0.05	−0.18	−0.09	0.15	0.27	0.15	−0.22	0.16	0.02	1.00																					
L_b	0.84	−0.21	−0.13	−0.17	0.23	−0.24	0.52	0.16	0.23	−0.55	−0.29	−0.13	−0.00	−0.33	−0.16	0.12	1.00																				
k_e	−0.18	0.10	0.19	0.21	−0.44	0.11	−0.40	−0.16	−0.18	0.35	0.50	0.34	0.01	0.26	0.13	−0.09	−0.57	1.00																			
k_c	−0.23	0.00	−0.09	0.23	−0.36	0.15	−0.28	−0.22	−0.18	0.31	0.55	0.30	−0.06	0.19	0.07	0.05	−0.54	0.76	1.00																		
L_c	0.89	−0.21	−0.16	−0.17	0.11	−0.24	0.50	0.17	0.23	−0.53	−0.24	−0.07	−0.00	−0.33	−0.18	0.10	0.97	−0.49	−0.45	1.00																	
S_c	−0.29	−0.09	−0.14	0.44	−0.27	0.42	−0.43	−0.30	−0.33	0.34	0.62	0.43	−0.03	0.23	0.08	0.36	−0.45	0.40	0.57	−0.42	1.00																
L_w	0.83	−0.24	−0.15	−0.17	0.21	−0.23	0.56	0.18	0.24	−0.53	−0.24	−0.10	−0.03	−0.36	−0.22	0.16	0.98	−0.53	−0.46	0.97	−0.43	1.00															
S_w	0.28	−0.08	−0.13	0.40	−0.24	0.44	−0.39	−0.27	−0.31	0.37	0.64	0.48	−0.09	0.25	0.09	0.39	−0.45	0.40	0.56	−0.41	0.98	−0.42	1.00														
E_w	−0.01	−0.57	−0.43	0.40	0.42	−0.23	0.26	−0.01	−0.02	−0.29	−0.20	−0.06	0.37	−0.56	−0.49	−0.25	0.10	−0.22	−0.12	0.08	−0.04	0.11	−0.06	1.00													
E_o	−0.05	−0.53	−0.41	0.35	0.47	−0.26	0.28	0.02	0.01	−0.25	−0.21	−0.07	0.33	−0.53	−0.46	−0.26	−0.06	−0.20	−0.12	0.03	−0.10	0.06	−0.11	0.99	1.00												
E_p	0.02	−0.56	−0.42	0.50	0.33	−0.20	0.13	−0.09	−0.06	−0.35	−0.21	−0.09	0.51	−0.56	−0.47	−0.23	0.16	−0.25	−0.13	0.14	−0.01	0.14	−0.06	0.94	0.90	1.00											
E_d	0.10	−0.47	−0.35	0.55	0.10	−0.08	−0.06	−0.18	−0.12	−0.38	−0.16	−0.08	0.60	−0.45	−0.38	−0.14	0.23	−0.25	−0.11	0.23	0.08	0.19	−0.00	0.67	0.58	0.88	1.00										
S_m	−0.32	−0.35	−0.32	0.74	−0.21	0.42	−0.49	−0.41	−0.40	0.12	0.58	0.44	0.42	−0.05	−0.18	0.25	−0.44	0.37	0.49	−0.41	0.74	−0.44	0.72	0.21	0.17	0.31	0.40	1.00									
s_i	−0.30	−0.09	−0.16	0.44	−0.25	0.42	−0.43	−0.33	−0.34	0.34	0.65	0.44	−0.01	0.21	0.08	0.33	−0.47	0.46	0.63	−0.43	0.97	−0.45	0.96	−0.03	−0.08	0.00	0.09	0.80	1.00								
t_w	0.63	−0.08	−0.06	−0.28	0.22	−0.20	0.47	0.13	0.22	−0.45	−0.23	−0.14	−0.11	−0.21	−0.09	0.33	0.86	−0.57	−0.48	0.82	−0.47	0.89	−0.45	−0.17	−0.18	−0.13	−0.06	−0.51	−0.49	1.00							
T_a	−0.15	0.51	0.43	−0.33	−0.38	0.31	−0.29	−0.02	−0.09	0.48	0.38	0.18	−0.42	0.59	0.47	0.19	−0.35	0.39	0.21	−0.33	0.20	−0.34	0.25	−0.79	−0.76	−0.87	−0.79	−0.03	0.21	−0.14	1.00						
P_a	−0.16	−0.04	−0.16	0.19	−0.25	0.10	−0.21	0.08	−0.04	0.38	0.37	0.26	0.01	0.12	0.15	0.08	−0.32	0.34	0.29	−0.27	0.32	−0.31	0.31	0.05	0.08	0.01	−0.06	0.44	0.36	−0.36	0.31	1.00					
W_m	−0.02	−0.44	−0.54	0.41	0.18	−0.10	0.06	−0.08	−0.01	−0.12	−0.02	0.02	0.30	−0.37	−0.25	−0.04	0.01	0.00	0.14	0.04	0.12	0.01	0.08	0.74	0.73	0.75	0.61	0.44	0.18	−0.20	−0.61	0.44	1.00				
P_s	−0.11	−0.33	−0.34	0.37	0.04	−0.11	−0.02	−0.04	−0.10	0.01	0.01	−0.01	0.26	−0.25	−0.16	−0.31	−0.17	0.08	0.14	−0.13	0.20	−0.16	0.16	0.75	0.73	0.70	0.51	0.40	0.22	−0.42	−0.42	0.51	0.72	1.00			
W_h	−0.03	−0.56	−0.57	0.46	0.35	−0.26	0.19	−0.02	0.05	−0.27	−0.17	−0.06	0.43	−0.54	−0.40	−0.09	0.09	−0.18	−0.01	0.08	−0.02	0.07	−0.06	0.82	0.81	0.87	0.74	0.34	0.01	−0.12	−0.79	0.23	0.91	0.65	1,00		
W_e	0.01	−0.61	−0.57	0.48	0.38	−0.29	0.23	0.02	0.09	−0.33	−0.17	−0.04	0.46	−0.61	−0.48	−0.12	0.14	−0.21	−0.04	0.12	−0.04	0.12	−0.09	0.84	0.82	0.89	0.77	0.31	−0.02	−0.09	−0.84	0.15	0.88	0.63	0.99	1.00	
W_p	−0.02	0.57	−0.57	0.46	0.33	−0.27	0.19	0.01	0.05	−0.28	−0.16	−0.03	0.42	−0.54	−0.40	−0.11	0.10	−0.18	−0.03	0.09	−0.03	0.08	−0.08	0.82	0.80	0.86	0.73	0.32	−0.01	−0.12	−0.78	0.24	0.90	0.65	1.00	0.99	1.00

4.1 Spring maximum runoff

Mean spring maximum runoff (MHq_w) could be best explained by tree stand ($F_s^{1/3}$, r = −0.68; F_c, r = −0.52), the altitude of the basin (E_w, E_o, E_p; r = 0.58, 0.61, 0.53, respectively), average snow cover (W_m, W_h, W_e, W_p; r = 0.52, 0.57, 0.54, 0.55, respectively), mean annual temperature (T_a, r = −0.49) and the percentage of open bog (B_o, r = 0.45). Some of the best and the most practical combinations are presented in equations (2) − (4).

$$MHq_w = -0.50\,F_s + 0.018\,(C + I_s)^2 - 1.2\,(C + I_s) + 0.29\,E_o + 126 \quad (2)$$
$R = 0.875$
$s_e = 19$

$$MHq_w = -0.91\,F_s + 0.33\,E_o + 21\,A^{-1/2} + 125 \quad (3)$$
$R = 0.885$
$s_e = 18$

$$MHq_w = -29\,F_s^{1/3} + 0.23\,E_o + 0.37\,W_m + 160 \quad (4)$$
$R = 0.880$
$s_e = 19$

The independent variables are significant at the < 0.1 per cent risk, except for $C + I_s$ in eq. (2) and E_o in eq. (4) (risk < 1 per cent). The variable W_m in eq. (4) has the T-value equal to 1.92, which is little less than 5 per cent risk level. The equation (2) is presented as a nomograph in Fig. 7.

Instantaneous spring maximum runoff ($MHq_{w\ inst}$) was best explained by tree stand ($F_s^{1/3}$, r = −0.74; F_c, r = −0.54), fine fractions of soil (G_c^2, r = 0.62; G_f^2, r = 0.60), the percentage of cultivated land (C^2, r = 0.60), drainage density (D_d, r = 0.49) and drainage area ($A^{-1/3}$, r = 0.41). Some combinations for $MHq_{w\ inst}$ are presented in equations (5)—(7).

$$MHq_{w\ inst} = 113\,A^{-1/3} - 1.9\,F_s + 0.34\,E_o + 158 \quad (5)$$
$R = 0.890$
$s_e = 34$

$$MHq_{w\ inst} = 106\,A^{-1/3} - 2.0\,F_s + 0.93\,W_m + 93 \quad (6)$$
$R = 0.896$
$s_e = 33$

$$MHq_{w\ inst} = 83\,A^{-1/3} - 1.6\,F_s + 0.013\,(C + I_s)^2 - 0.63\,(C + I_s) + 0.99\,W_m + 82 \quad (7)$$
$R = 0.903$
$s_e = 34$

The independent variables are significant at the < 0.1 per cent risk, except for W_m in eq. (7) (risk < 1 per cent) and $C + I_s$ in eq. (7) (T-value = 1.18).

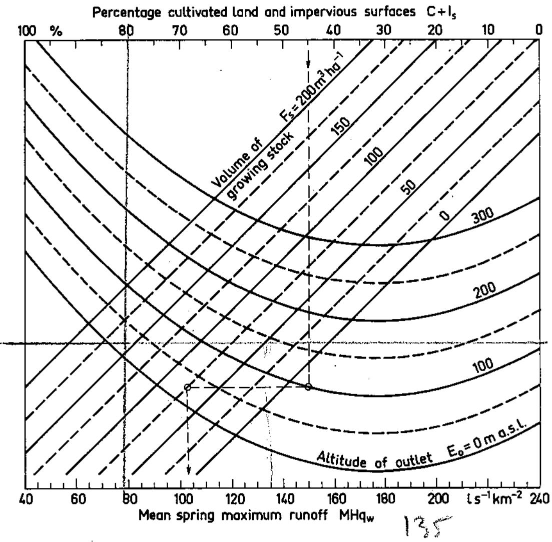

Fig. 7. A nomograph for the mean value of the spring maximum runoff $MHq_w = 0.018\,(C+I_s)^2 - 1.2\,(C+I_s) + 0.29\,E_o - 0.50\,F_s + 126$.

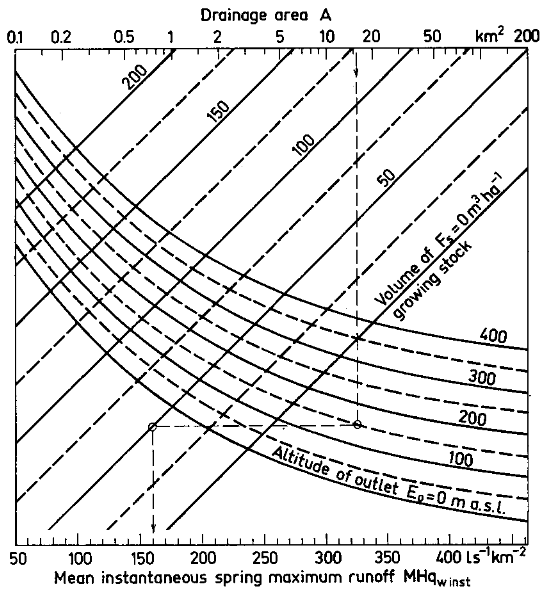

Fig. 8. A nomograph for the mean value of the instantaneous spring maximum runoff $MHq_{w\ inst} = 113\,A^{-1/3} + 0.34\,E_o - 1.9\,F_s + 158$.

The equation (5) is presented as a nomograph in Fig. 8.

The increase of 1 $m^3\,ha^{-1}$ in the growing stock decreased the instantaneous spring maximum by about 2 l s^{-1} km^{-2} (eqs. (5)—(6)). The percentage of impermeable surfaces (I_s) explained $MHq_{w\ inst}$ well especially in quadratic form, but because of the narrow variation range — from 0 to 8 per cent — it was rejected from the final models. The cubic root of F_s did not improve models with two or more variables, although it alone explained $MHq_{w\ inst}$ well.

For the spring maximum runoff with return period of 20 years (Hq_w 1/20) the best variables were tree stand ($F_s^{1/3}$ and F_c, r = −0.68 and − 0.53), the percentages of open bog (B_o, r = 0.44), forest (F, r = −0.43), coarse soils (G_r, r = −0.41) and cultivated land (C^2, r = 0.41). In equations (8) — (9) combinations for Hq_w1/20 are presented.

$$Hq_w 1/20 = -1.8\ F_s + 0.39\ E_o + 48\ A^{-1/2} + 257$$
$$R = 0.817 \quad (8)$$
$$s_e = 42$$

$$Hq_w\ 1/20 = -1.2\ F_s - 1.2\ F + 0.57\ E_o + 43\ A^{-1/2} + 278$$
$$R = 0.845 \quad (9)$$
$$s_e = 40$$

The variables in the equations are significant (risk < 0.1 per cent), except for E_o in eq. (8), F_s in eq. (9) (risk < 1 per cent) and F in eq. (9) (risk < 5 per cent). The equation (8) is presented as a nomograph in Fig. 9.

The instantaneous spring maximum runoff with return period of 20 years ($Hq_{w\ inst}$1/20) was best explained by fine fractions of soil (G_c^2, r = 0.73; G_f^2, r = 0.72), field percentage (C^2, r = 0.71), drainage density (D_d, r = 0.58) and tree stand ($F_s^{1/3}$, r = −0.77; F_c, r = −0.55). Some of the best combinations are shown in eqs. (10) — (12).

$$Hq_{w\ inst}1/20 = 129\ A^{-1/3} - 133\ F_s^{1/3} + 699$$
$$R = 0.877 \quad (10)$$
$$s_e = 74$$

$$Hq_{w\ inst}1/20 = 173\ A^{-1/3} - 3.3\ F_s + 0.054\ (C + I_s)^2 - 3.6\ (C + I_s) + 389$$
$$R = 0.890 \quad (11)$$
$$s_e = 72$$

$$Hq_{w\ inst}1/20 = 113\ A^{-1/3} - 1.7\ F_s + 0.14\ G_f^2 - 4.7\ G_f + 3.8\ B_o + 288$$
$$R = 0.913 \quad (12)$$
$$s_e = 65$$

The independent variables are significant (risk < 0.1 per cent), except for G_f in eq. (12) (risk < 1 per cent) C + I_s in eq. (11) and A, F_s, B_o in eq. (12) (risk < 5 per cent). The equation (11) is presented as a nomograph in Fig. 10.

The equation (12) explains 83 per cent of the variance of $Hq_{w\ inst}$1/20. A number of equations having a degree of determination of 90 per cent or more were rejected, because the quadratic term of impervious surfaces (I_s) was not wanted to be included due to its narrow variation range.

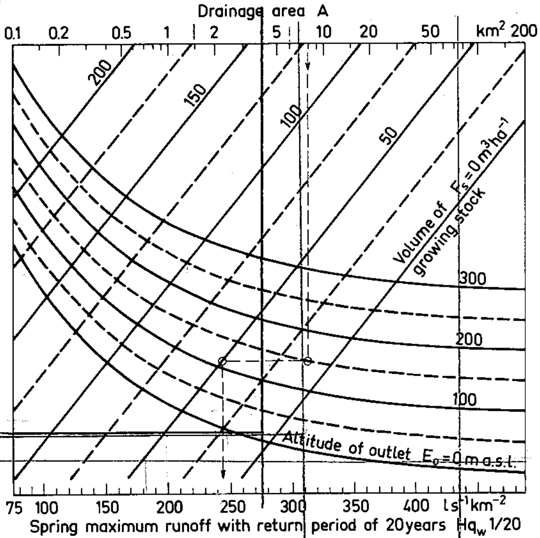

Fig. 9. A nomograph for the spring maximum runoff with return period of 20 years Hq_w 1/20 = 48 $A^{-1/2}$ +0.39 E_o −1.8 F_s +257.

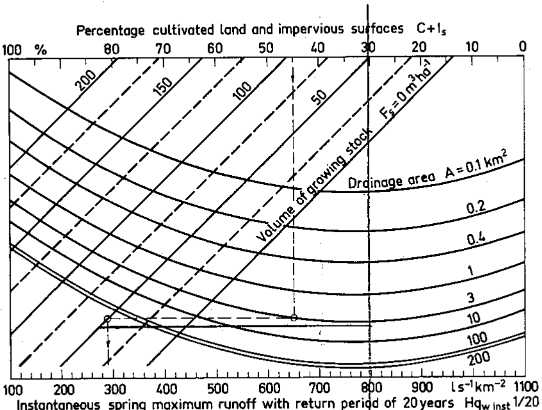

Fig. 10. A nomograph for the instantaneous spring maximum runoff with return period of 20 years $Hq_{w\ inst}$ 1/20 = 173 $A^{-1/3}$ + 0.054 $(C + I_s)^2$ − 3.6 $(C+I_s)$ − 3.3 F_s + 389.

4.2 Summer maximum runoff

Mean summer maximum runoff (MHq_s) was best explained by the percentages of fine soils (G_f^2, r = 0.45; G_c^2, r = 0.47), summer precipitation (P_s, r = 0.50) and drainage density (D_d, r = 0.41). Water equivalent of snow also indicated increased summer maximum runoff. The basin average of summer maximum could not be explained satisfactorily, as can be stated from the following equations.

$$MHq_s = 0.016\,(G_c + I_s)^2 + 0.13\,E_o + 0.055\,P_a - 8 \qquad (13)$$
$$R = 0.761$$
$$s_e = 10.0$$

$$MHq_s = 0.57\,G_c + 0.15\,E_o + 1.42\,I_s^2 - 9.0\,I_s - 0.26\,B + 38$$
$$R = 0.852 \qquad (14)$$
$$s_e = 8.3$$

The variables are significant (risk $<$ 0.1 per cent), except for B in eq. (14) (risk $<$ 5 per cent) and P_a in eq. (13) (T-value 1.94). The equation (13) is presented as a nomograph in Fig. 11.

The percentage of impermeable surfaces, in a quadratic form especially, was rather decisive in explaining the variance of MHq_s. The narrow data base, mentioned before, makes the regression coefficients of I_s^2 unstable and high. Therefore I_s greater than 8 per cent, the highest value in the data, should not be used.

The instantaneous summer maximum runoff ($MHq_{s\ inst}$) was best explained by drainage area ($A^{-1/3}$, r = 0.76), the percentage of fine soils (G_f^2, r = 0.70; G_c^2, r = 0.62), drainage density (D_d, r = 0.68) and the percentage of cultivated land (C^2, r = 0.55). Some of the combinations are shown in eqs. (15) – (17).

$$MHq_{s\ inst} = 58\,A^{-1/3} + 0.045\,(G_f + I_s)^2 - 1.6\,(G_f + I_s) + 33$$
$$R = 0.858 \qquad (15)$$
$$s_e = 30$$

$$MHq_{s\ inst} = 47\,A^{-1/3} + 0.052\,G_f^2 - 2.1\,G_f + 11.3\,I_s + 29$$
$$R = 0.869 \qquad (16)$$
$$s_e = 29$$

$$MHq_{s\ inst} = 52\,A^{-1/3} + 0.017\,C^2 - 0.73\,C + 10.6\,I_s + 24$$
$$R = 0.825 \qquad (17)$$
$$s_e = 33$$

The variables are significant (risk $<$ 0.1 per cent), except for A and I_s in eq. (16), A in eq. (17) (risk $<$ 1 per cent), I_s in eq. (17) (risk $<$ 5 per cent) and C in eq. (17) (T-value = 1.64). The equation (15) is presented as a nomograph in Fig. 12.

The inclusion of the percentage of impervious surfaces would improve the models; e.g. a

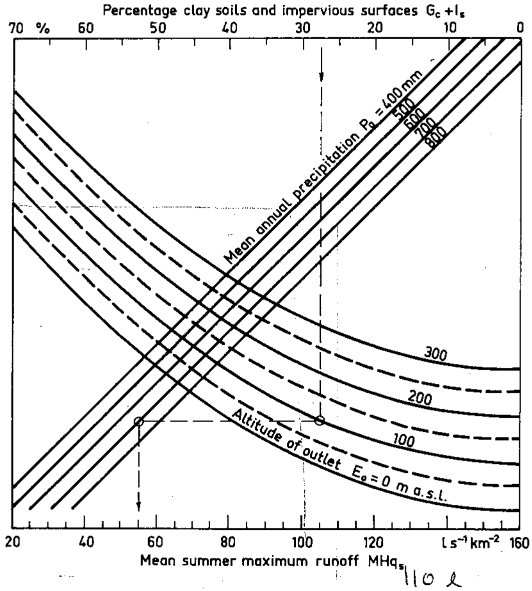

Fig. 11. A nomograph for the mean value of the summer maximum runoff $MHq_s = 0.016\,(G_c + I_s)^2 + 0.13\,E_o + 0.055\,P_a - 8$.

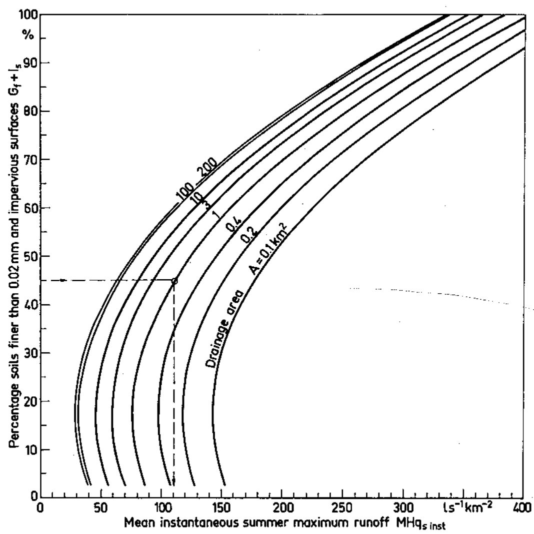

Fig. 12. A nomograph for the mean value of the instantaneous summer maximum runoff $MHq_{s\ inst} = 58\,A^{-1/3} + 0.045\,(G_f + I_s)^2 - 1.6\,(G_f + I_s) + 33$.

combination of $A^{-1/3}$, G_c^2, G_c, I_s^2 and I_s explains 91 per cent of the variance of $MHq_{s\ inst}$, but it was rejected from the final equations.

The summer maximum runoff with return period of 20 years ($Hq_s 1/20$) was best explained by the percentage of fine soils (G_f^2, r = 0.75; G_c^2, r = 0.71), drainage density (D_d, r = 0.71) the percentage of cultivated land (C^2, r = 0.70) and drainage area ($A^{-1/3}$, r = 0.61). Equations (18) — (20) show some combinations for Hq_s 1/20.

$$Hq_s\ 1/20 = 0.037\ (G_f + I_s)^2 + 0.97\ P_s - 88 \qquad (18)$$
$R = 0.843$
$s_e = 29$

$$Hq_s 1/20 = 0.030\ C^2 - 1.1\ C + 0.31\ P_a + 9.2\ I_s - 100 \qquad (19)$$
$R = 0.849$
$s_e = 30$

$$Hq_s\ 1/20 = 0.058\ (G_f + I_s)^2 - 1.6\ (G_f + I_s) + 0.29\ P_a - 81 \qquad (20)$$
$R = 0.861$
$s_e = 28$

The variables are significant (risk < 0.1 per cent), except for P_a in eq. (19) (risk < 1 per cent) and I_s in eq. (19) (risk < 5 per cent). The equation (20) is presented as a nomograph in Fig. 13.

The instantaneous summer maximum runoff, with return period of 20 years ($Hq_{s\ inst}$ 1/20) was best explained by drainage area ($A^{-1/3}$, r = 0.84), drainage density (D_d, r = 0.77) and the percentage of fine soils (G_f^2, r = 0.78; G_c^2, r = 0.70). Some combinations are presented in equations (21) — (23).

$$Hq_{s\ inst}\ 1/20 = 302\ A^{-1/3} + 0.11\ (G_f + I_s)^2 - 12 \qquad (21)$$
$R = 0.917$
$s_e = 107$

$$Hq_{s\ inst} 1/20 = 317\ A^{-1/3} + 0.19 (G_f + I_s)^2 - 5.2\ (G_f + I_s) + 19\ b_i - 24 \qquad (22)$$
$R = 0.943$
$s_e = 92$

$$Hq_{s\ inst} 1/20 = 394\ A^{-1/3} + 0.052\ C^2 + 21\ b_i - 83 \qquad (23)$$
$R = 0.907$
$s_e = 115$

The variables in the equations are significant (risk < 0.1 per cent), except for b_i in eqs. (22) and (23) (risk ~ 5 per cent). The equation (22) is presented as a nomograph in Fig. 14.

The dependent variable could be explained with a high degree of determination, but a number of the best combinations had to be rejected due to unacceptable distribution of the residuals.

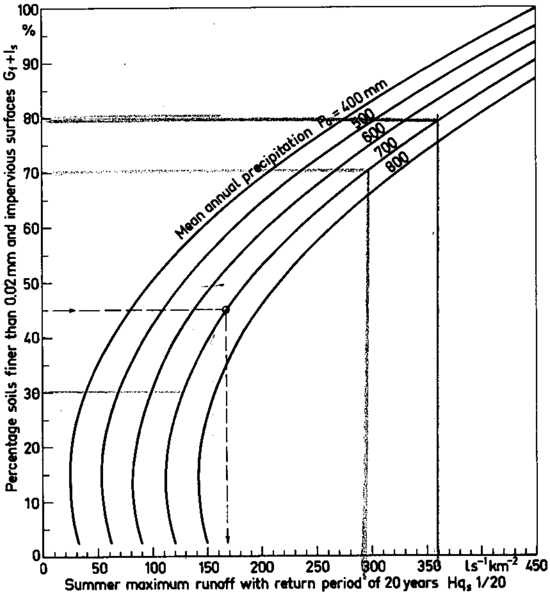

Fig. 13. A nomograph for the summer maximum runoff with return period of 20 years $Hq_s\ 1/20 = 0.058\ (G_f+I_s)^2 - 1.6\ (G_f+I_s)+0.29\ P_a - 81$.

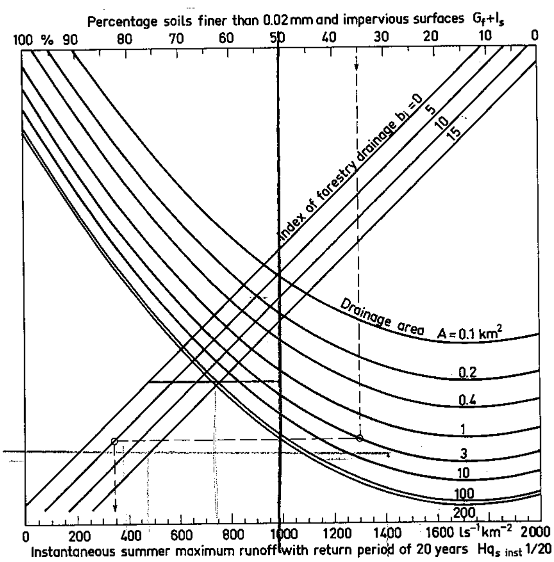

Fig. 14. A nomograph for the instantaneous summer maximum runoff with return period of 20 years $Hq_{s\ inst}\ 1/20 = 317\ A^{-1/3}+0.19\ (G_f+I_s)^2-5.2\ (G_f+I_s) + 19\ b_i-24$.

4.3 Runoff ratios

4.31 Spring

The instantaneous spring maximum runoff $MHq_{w\ inst}$ was on average 1.31 times the daily spring maximum MHq_w with a standard deviation of 0.23. Equation (24) explains 70 per cent of the total variance of this ratio.

$$MHq_{w\ inst}/MHq_w = 0.28\ A^{-1/3} + 0.0044\ (C + I_s) + 1.05$$
$$R = 0.837 \quad (24)$$
$$s_e = 0.13$$

Both variables are significant at the < 0.1 per cent risk.

The ratio of Hq_w 1/20 and MHq_w was on average 1.91 and a standard deviation 0.26. The increase of average snow cover decreased the ratio, which could not, however, be explained satisfactorily, eq. (25).

$$Hq_w 1/20/MHq_w = -0.0031\ W_p - 0.0041\ G_r + 2.53$$
$$R = 0.636 \quad (25)$$
$$s_e = 0.21$$

The ratio of $Hq_{w\ inst}$ 1/20 and $MHq_{w\ inst}$ was on average 1.92 and a standard deviation of the ratio 0.27. Snow cover and coarse soils decreased also this ratio, as shown in eq. (26).

$$Hq_{w\ inst} 1/20/MHq_{w\ inst} = -\ 0.0058\ W_m - 0.0048\ G_r + 2.84$$
$$R = 0.681 \quad (26)$$
$$s_e = 0.21$$

The snow variables (W_p in eq. (25) and W_m in eq. (26) are significant at the < 1 per cent and < 0.1 per cent risk, respectively, G_r at the < 5 per cent risk in the both equations.

The ratio of $Hq_{w\ inst}$ 1/20 and MHq_w was on average 2.50 and a standard deviation 0.58. Equations (27) – (29) show some combinations for this ratio.

$$Hq_{w\ inst}\ 1/20/MHq_w = 0.83\ A^{-1/3} - 0.015\ F + 2.89$$
$$R = 0.854 \quad (27)$$
$$s_e = 0.31$$

$$Hq_{w\ inst} 1/20/MHq_w = 0.60\ A^{-1/3} - 0.010\ F + 0.011\ G_f + 2.59$$
$$R = 0.882 \quad (28)$$
$$s_e = 0.29$$

$$Hq_{w\ inst}\ 1/20/MHq_w = 0.80\ A^{-1/3} - 0.011\ F_s + 0.20\ T_a + 2.01$$
$$R = 0.866 \quad (29)$$
$$s_e = 0.31$$

The variables in the equations are significant at the < 0.1 per cent risk, except for F (risk < 1 per cent) and G_f (risk < 5 per cent) in eq. (28).

4.32 Summer

The ratio of $MHq_{s\ inst}$ and MHq_s was on average 1.53 and a standard deviation 0.67. The ratio could be explained with a high degree of determination, as shown in equations (30) – (31).

$$MHq_{s\ inst}/MHq_s = 1.30\ A^{-1/3} + 0.74$$
$$R = 0.927 \quad (30)$$
$$s_e = 0.26$$

$$MHq_{s\ inst}/MHq_s = 1.15\ A^{-1/3} + 0.10\ I_s + 0.70$$
$$R = 0.951 \quad (31)$$
$$s_e = 0.21$$

The variables in these equations are significant (risk < 0.1 per cent).

The ratio of Hq_s 1/20 and MHq_s was on average 2.73 and a standard deviation 0.61. The equation (32) explained 66 per cent of the variance of the ratio.

$$Hq_s\ 1/20/MHq_s = 0.19\ T_a + 0.00013\ C^2 + 0.096\ S_w + 2.00$$
$$R = 0.811 \quad (32)$$
$$s_e = 0.37$$

The variable S_w is significant at the < 1 per cent risk, the others at the < 0.1 per cent risk.

The ratio of $Hq_{s\ inst}$ 1/20 and $MHq_{s\ inst}$ was on average 3.05 and a standard deviation 0.99. The ratio was increased by drainage density and high annual temperature (T_a), but could not be explained satisfactorily (eq. 33).

$$Hq_{s\ inst}\ 1/20/MHq_{s\ inst} = 0.42\ T_a + 0.00068\ (C + I_s)^2 - 0.052\ C + 2.20$$
$$R = 0.732 \quad (33)$$
$$s_e = 0.71$$

In this equation C is significant at the < 1 per cent risk, while the others at the < 0.1 per cent risk.

The ratio of $Hq_{s\ inst}$ 1/20 and MHq_s was on average 4.97 with a standard deviation of 3.70. The ratio could be explained well, as shown in equations (34) – (35).

$$Hq_{s\ inst}\ 1/20/MHq_s = 7.3\ A^{-1/3} + 0.53$$
$$R = 0.941 \qquad (34)$$
$$s_e = 1.27$$

$$Hq_{s\ inst}\ 1/20/MHq_s = 6.7\ A^{-1/3} + 0.048\ G_f + 0.32\ b_i - 0.36$$
$$R = 0.964 \qquad (35)$$
$$s_e = 1.03$$

The variables in these equations are significant (risk < 0.1 per cent), except for b_i in eq. (35) (risk < 1 per cent).

4.4 Discussion

The statistical characteristics of both spring and summer maximum runoff could be explained at a rather satisfactory level using only physiographic characteristics of the basins and some climatological factors, which are readily available beforehand. From a practical point of view this is important considering the design of hydraulic engineering works for unobserved basins.

To ensure the applicability of the equations obtained, the residuals of the models were analysed (Figs. 15 and 16). On this basis and because of the skewness of some transformations of the independent variables, a number of equations were rejected. A considerable number of them fitted to the data better than the respective equations presented here. It is still to be noted, however, that the independent variables should not be used for practical planning much beyond the range of the data base.

The peaked tendency and the extremity of the maximum runoff, i.e. ratios of the instantaneous to daily and the ratio of the exceptional to mean maximum were affected by many of the same factors. Those characteristics were especially promoted by fine soils (G_f, G_c), cultivated land (C), impervious surfaces (I_s), drainage network (B_d, b_i, D_d), slope of the basin (S_c, S_w, S_m, s_i) and high annual mean temperature (T_a). On the other hand the extremity and the peaked tendency were decreased by the increases in drainage area (A, L_h, L_c, L_w), in coarse soils (G_r), in altitudes (E_o, E_w, E_p) and in abundance of snow (W_m, W_h, W_e, W_p).

The most effective factors influencing the exceptional spring maximum, compared with mean maximum, were the amounts of snow and coarse soils, both of which tended to decrease this variation. An abundance of fine soils and a small drainage area respectively were the most important factors in sharpening the peak of spring flood.

For summer the exceptional maximum as compared with the mean was most affected by the annual temperature and drainage density. Respectively the drainage area alone explained more than 85 per cent of the variance of the peaked tendency for the summer flood.

In general the peaked tendency of flood could be much better explained than the relationship between exceptional maximum and mean maximum. This was the case both for spring and for summer.

Some of the characteristics evidently have a

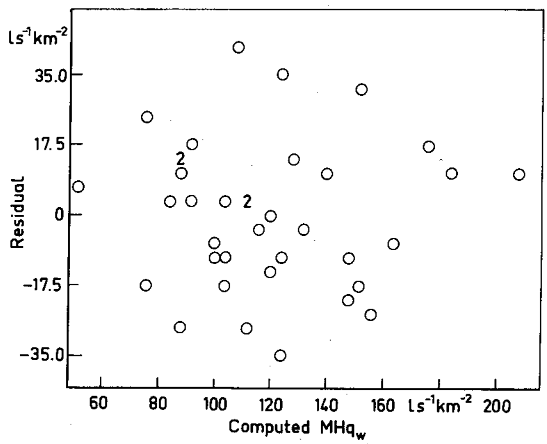

Fig. 15. An example of a satisfactory distribution of the residuals. The equation $MHq_w = 0.018\ (C+I_s)^2 - 1.2\ (C+I_s) - 0.50\ F_s + 0.29\ E_o + 126$, R = 0.875, has been used.

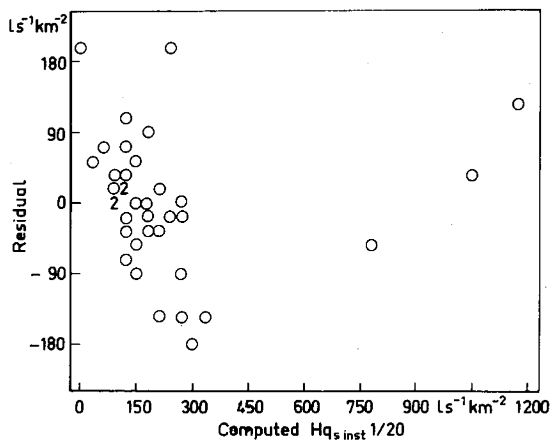

Fig. 16. An example of an unsatisfactory distribution of the residuals. The equation Hq_s inst 1/20 = $477\ A^{-1/2} + 5.6\ I_s^2 - 109\ S_w + 57$, R = 0.944, has not been accepted.

nature of a multiple coefficient. Such is e.g. drainage area, as shown in literature (e. g. Kaitera 1939, Renqvist 1933). In this context multiple combinations were not used, however, because the significance of the individual independent variables was wanted to be compared. The polynomial models used in this study are not necessarily physically-based, but they can be considered acceptable for practical purposes and for giving good suggestions for further research. In later studies multiple combinations should be tested.

Restrictions of regression analysis have been widely discussed in literature (e.g. Mustonen 1965c, Yevjevich 1972, Daniel and Wood 1980). Especially have the difficulties risen by intercorrelations of the independent variables been pointed out. Strictly speaking regression analysis should not be employed in such a case at all, if mathematical orthodoxy is followed. In hydrological phenomena, however, the intercorrelations are inevitable, and no practical solution exists to produce useful combinations of parameters, i.e. design models, except for regression analysis. On the other hand, the main purpose, also in this study, is to obtain combinations of readily available variables to explain satisfactorily the variation of a certain runoff quantity, but not that much to investigate the physical relationships. For these reasons the use of regression analysis can be considered justified.

The use of regression analysis also presupposes other requirements, such as the normality of the distribution of the variables and the residuals. An independent variable should also have a range wide enough in order to be meaningful in the regression equations. Due to these requirements a number of transformations and equations had to be rejected. Totally more than one thousand combinations of variables were tested.

The importance of the individual independent variables can be summarized as follows.

The **drainage area** (A) did not markedly affect the daily mean maxima, but was a strong independent variable for the instantaneous and unusual maxima of the smallest basins. This was supported by the fact that area did not appear in the models developed without the three smallest basins (basins 11—13). These results can be considered logical, if the fact is taken into account that, in the case of basins of this size, all water from snowmelt and rainfall comes to the measuring point during one day (Mustonen 1965 c). For summer maxima the areal conciseness, on the other hand, may produce large daily maxima in the smallest areas due to the dependence of rainfall intensity on area. The best transformation of area was generally $A^{-1/3}$, which emphasizes the exceptionality of the smallest basins ($A < 1$ km^2). Almost as good was $A^{-1/2}$, which had, however, a skewer distribution than $A^{-1/3}$ or $A^{1/3}$.

For $Hq_{s\ inst}$ 1/20 the use of $A^{-1/3}$, $A^{-1/2}$, ln A and their inverse values tended to result in an unsatisfactory distribution of the residuals. For this reason the linear term of A was added, but it resulted in an illogical combination and could not be accepted.

Drainage area was the most effective independent variable in explaining the ratios of the exceptional to average and of the instantaneous to daily maximum runoff, i.e. the extremity and the peaked tendency of the basin and flood. The transformation $A^{-1/3}$ alone explained more than 85 per cent of the variances of the ratios $MHq_{s\ inst}/MHq_s$ and $Hq_{s\ inst}1/20/MHq_s$.

The **percentage of cultivated land** (C) increased in higher percentages especially instantaneous maxima both for spring and summer. The quadratic transformation appeared better than the mere linear one as shown earlier by Kaitera (1939) and Mustonen (1965 c) for the spring maximum. A general relative form for C was $-C + 0.017\ C^2$ for the daily spring maximum, which is somewhat less steep than those presented earlier. The minimum is reached at 29 per cent of C, when the relative decrease of spring maximum runoff is 13 per cent of the mean. The maximum relative increase was 59 per cent for 100 per cent cultivated land. The minimum presented by Kaitera occurred at about 15 per cent and that by Mustonen at 24 per cent.

The distribution of C and especially that of C^2 was rather skew and this may influence the results. However, the regression coefficients of C and C^2 were notably stable in different combinations and for different dependent variables. When the regression equations $Hq = f(C, C^2)$ were computed, the relative coefficients of the quadratic term were, with a value of C equal to -1, for MHq_w, $MHq_{w\ inst}$, Hq_w 1/20 and $Hq_{w\ inst}$ 1/20: 0.013, 0.018, 0.015, 0.020, respectively and for MHq_s to $Hq_{s\ inst}$ 1/20: 0.017, 0.029, 0.031 and 0.026, respectively. Hence the relative influence of the field percentage for the summer maximum runoff was greater than for the spring maximum, although C appeared in the spring models, but was substituted by fine soils in the summer models.

As could be expected, the field percentage increased the extremity and the peaked tendency of the basin. This was shown clearly in the ratios of the instantaneous to daily and of the exceptional to average, which were the greater, the more cultivated land there was in the basin. The increase of about three per cent in field percentage caused the increase of one percent in the ratio of $MHq_{w\ inst}/MHq_w$.

The **percentage of sub-drained field** (C_s) had no clear effect on maximum runoff, and it did not appear in the models, either. In chapter 6.3 results of an experimental study support this finding. The plot of C_s versus MHq_w to $Hq_{s\ inst}$ 1/20 showed a relationship resembling that of C, but weaker. It is to be noted, however, that the small variation of C_s restricts the explaining ability of this variable.

The **percentage of forest** (F) especially decreased spring maximum runoff but also the summer maximum. The primary reasons for the reduction are evidently the delay in the snowmelt conditions caused by forest and the permeable soils associated with forest (r_{F,G_r} = 0.79). However, forest percentage did not generally appear in the models due to a better independent variable, F_s.

Forest also decreased the extremity and the peaked tendency of maximum runoff, especially for the ratios of spring maximum runoff $MHq_{w\ inst}/MHq_w$, $Hq_{w\ inst}1/20/MHq_{w\ inst}$ and $Hq_{w\ inst}1/20/MHq_w$.

The **percentage of swampland** (B) had a decreasing effect on summer maximum runoff. It also appeared in some summer models. For spring maximum runoff there was no significant correlation; B did not come to these models, either.

Swamplands decreased the extremity of the maximum runoffs. Especially the runoff ratios of the summer maxima were decreased with the increase in the percentage of swamplands.

The **percentage of open bog** (B_o) increased spring maximum runoff, but decreased summer maximum. It also appeared in some spring models. In an open bog, snow is accumulated in an abundance (Mustonen 1965 a), and the conditions of snowmelt resemble those for cultivated land. It has been also presented (Kaitera 1939) that snowmelt waters are stored behind the snow banks of the bog and then abruptly discharged in high peaks. The decreasing effect on summer maxima could be caused by the storage capacity of such bog, which might cut the peaks to some extent. This conclusion is substituted by the runoff ratios of summer maximum runoffs, which are decreased by the increase of open bog. On the other hand, no influence caused by open bog on the extremity of spring runoffs could be observed.

The **percentage of forest-drained area** (B_d) did not show strong correlation with maximum runoff. It came to some summer models of Hq_s 1/20 with an increasing effect of about 1.5 l s^{-1} km^{-2} for one per cent's drained area. It seems evident that the decreasing effect of swampland (B_o and B) on summer maxima was removed by draining. On spring maximum runoff no influence of forestry drainage was observed.

The percentage of forestry drainage was in negative correlation with runoff ratios; however, to a smaller degree than the percentage of peatlands (B). This could be interpreted as a small growth in the extremity of runoff maxima.

The influence of **the index of forestry drainage** (b_i) did not differ from that of the mere drainage percentage, although the time factor was included in the index. However, b_i improved the residual distribution of the $Hq_{s\ inst}$ 1/20 equations in such a way that it was included in some final models.

The **percentage of impervious surfaces** including open bedrocks (I_s) explained the summer maximum runoff well. Because of the narrow variation range of I_s, the quadratic transformation, which would have been much better, was avoided in the final equations. Generally I_s was added to the field percentage (C) or to the percentage of fine soils (G_f and G_c). The combination 1.2 $(I_s)^2$ — 6.0 I_s, in equations of MHq_s would result in 11 400 l s^{-1} km^{-2} of runoff, if the drainage basin were completely impermeable. This is not probable, although the maximum 20 minutes rainfall with return period of 20 years amounts to 16 700 l s^{-1} km^{-2} in Finland (Kuusisto 1980). In an urban area, 67 per cent paved, the maximum peak of 5400 l s^{-1} km^{-2} has been measured (Melanen and Laukkanen 1981).

The increase of impervious surfaces also increased the extremity of maximum runoffs.

The **drainage density of main ditches** (D_d) showed a strong increasing effect on maximum runoff, especially those of summer. However, in the models it was mostly substituted by the drainage area (A) and field percentage (C). The regression coefficients of D_d for Hq_s 1/20 and $Hq_{s\ inst}$1/20 were approximately 36, while the mean density of main channels of the basins was 1.5 **km^{-1}**.

Drainage density also strongly increased the extremity of the basins, both for summer and spring maximum runoffs. For example, if the drainage density increased from one to two km^{-1}, the ratio of $MHq_{w\ inst}/MHq_w$ increased by 15 per cent.

The **volume of growing stock** (F_s) decreased spring maximum runoff and was one of the best independent variables for it. The increase of 1 m^3 ha^{-1} in tree stand caused a decrease of 0.7 l s^{-1} km^{-2} in the daily mean maximum, but a somewhat greater decrease in the instantaneous or exceptional maximum runoff. The plot of F_s vs. Hq showed a slight curvature. Of the several transformations tested, the third to ninth roots of F_s proved to be the best ones. The smaller roots better represented daily spring maxima; the highest ones fitted best to the instantaneous summer maxima. The root transformations improved a few models consisting of only one or two independent variables, but not the models containing more variables. As stated before, tree stand causes delay in snowmelt and also positively correlates with coarse soils, which both tend to decrease runoff peaks.

The **coverage of tree stand** (F_c) had much of a similar effect on the spring maximum runoff as the volume of growing stock. Usually information on the coverage of tree stand is not as easily available as that of F_s. For this reason it was omitted from the models, although it would have been even better for $MHq_{w\ inst}$ and $Hq_{w\ inst}$ 1/20.

The **percentage of coarse soils** (G_r) decreased both spring and summer maximum runoffs. It was a slightly weaker independent variable than the indices of fine soils (G_f and G_c) and did not enter the best models.

The coarse soils also reduced the extremity of maximum runoff. The index of coarse soils was also formed without fine sand moraine, but it proved to be a weaker independent variable than G_r. On the other hand, coarse soils better refer to low flows, on physical basis.

The **percentage of fine soils** (G_f) and the **percentage of clay soils** (G_c) correlated well with the summer maximum and the instantaneous spring maximum runoff. The increasing effect was best indicated in the quadratic transformation, such as e.g. $0.05\ G_f^2 - 1.1\ G_f$ for Hq_s 1/20. The quadratic transformation of G_c was avoided in the final equations because of the skewness of G_c^2 -distribution. Furthermore, G_f generally explained the variance better than G_c did. The influence of fine soils to a high degree equalled with that of the field percentage (C), which is natural considering the close correlation between them ($r = 0.86$). However, fine soils tended to especially explain summer maxima, while the field percentage explained those of spring. In the final models combinations of $G_f + I_s$ and $G_c + I_s$ were also used in order to obtain a better normality of the distribution of the independent variable. The distributions of the residuals were satisfactory for the mere G_f- and G_c -models as well.

Fine soils clearly increased the extremity of maximum runoff; more clearly than coarse soils reduced it.

The **percentage of gravel and gravel moraine** (G_g) did not show any notable effect on maximum runoff. For the most part this can be counted on the small variation of G_g.

The **length of the basin** (L_b) had a decreasing effect on the instantaneous summer maximum runoff. It evidently means a long travelling time for runoff and had, in fact, a closer correlation with maximum runoff than the drainage area (A) in linear form did. In the models L_b stayed away, when the transformations of drainage area were included.

The length reduced the extremity and the peaked tendency of maximum runoff, but did not generally enter the best models of runoff ratios, either.

The **elongation ratio of the basin** (k_e) affected the instantaneous summer maximum runoff in such a way that the bigger k_e, i.e. the less elongated, the greater and more peaky the maximum runoff. It was included in some summer models.

For the extremity the effect was parallel; the rounder the basin, the more extreme the maximum runoff.

The **circularity of the basin** (k_c) had a similar relationship with the maximum runoff as the elongation ratio did, which was expectable. It did not enter the best models. The circularity also increased the extremity and the peaked tendency of maximum runoff.

The **length of the main channel** (L_c) correlated very strongly with the length of the basin ($r = 0.97$). Of course the influence on runoff was almost identical with that of L_b and the opposite to k_e and k_c. The same holds true for the runoff ratios.

The **mean slope of the main channel** (S_c) increased the instantaneous summer maximum. Because of the skewness of its distribution it was generally rejected from the final models.

The slope increased the extremity and the peaked tendency of summer maxima remarkably.

The increase in **the distance from the centre of gravity to the outlet** (L_w) decreased the summer maximum runoff, but had not any notable effect on the spring maxima. It also reduced the extremity and the peaked tendency of maximum runoff, especially those for summer. The influence, naturally, is parallel to that of the drainage area.

The **slope from the centre of gravity to the outlet** (S_w) increased the instantaneous summer maximum runoff. Due to the skewness of the distribution it was generally rejected from the final equations. The slope also increased the extremity and the peaked tendency of summer maximum runoff, especially.

The **altitude of the basin** (E_w, E_o and E_p) was one of the best independent variables explaining spring maximum runoff especially. The most easily available of them, the altitude of the outlet (E_o)

was in most cases also the best one. An increase of 10 meters in the altitude (E_o) resulted in an increase of 4 l s^{-1} km^{-2} in spring maximum runoffs. The absolute increase almost equalled for various quantities of spring maximum runoff. Hence the relative influence of the altitude was greatest for the daily maximum spring runoff, which can also be seen in the correlation coefficients.

The altitude reduced the extremity of maximum runoffs. Especially the extremity of summer maxima decreased with the rise of the altitude. For the extremity and for the peaked tendency the maximum altitude was more effective than the altitude of the outlet.

The altitude has much the nature of an overall index: high altitudes generally mean in Finland a lot of snow ($r = 0.82$), a low percentage of cultivated land ($r = -0.61$) and fine soils ($r = -0.55$), and low annual temperature ($r = -0.76$).

The **maximum variation in the altitude** (E_d) behaved in the same way as the altitude indices did. It explained, however, much less of the variances of the maximum runoffs than the altitudes and thus did not enter the best models. The increase in the altitude difference reduced the extremity and the peaked tendency similarly to the absolute altitude. It is explained mainly by the high correlation between the difference and the altitude ($r = 0.88$).

The **mean slope of the basin** (S_m) increased the summer maxima, but decreased the spring maxima, according to the correlation coefficients. The mean slope did not prove to be as good an independent variable, as could be expected and did not come to the final equations. It was not effective in explaining the runoff ratios, either, although it increased the peaked tendency of exceptional summer maxima.

The **slope index** (s_i) increased the instantaneous summer maximum runoff, but was insignificant for the other runoff quantities. As far as the extremity and the peaked tendency of runoff is in concern, the slope index acted parallelly to the mean slope, but with much closer correlation ($r = 0.75$ and 0.71 for $MHq_{s\ inst}$ and $Hq_{s\ inst}$ 1/20 vs. MHq_s, respectively). Especially was the peaked tendency of summer maximum runoff increased by the slope index.

The **time of flow from the centre of gravity** (t_w) appeared to be a significant variable for summer maxima, especially. It would have improved the degree of determination of those models, but it was not included due to its laborious calculation. The shortening in the time of flow increased the peaked tendency of the maximum runoffs, both for spring and summer.

The **mean annual air temperature** (T_a) decreased the daily spring maximum by about 3 l s^{-1} km^{-2} for 1°C. It was not as good as the altitude or snow cover and did not enter the best models. On the other hand the mean annual temperature remarkably increased the extremity and the peaked tendency of the maximum runoffs.

The **mean annual precipitation** (P_a) entered some of the equations for summer maximum runoff. An increase of ten millimeters in P_a caused an increase of about 3 to 4 l s^{-1} km^{-2} in the summer maximum with return period of 20 years. The mean precipitation had no significant effect on the extremity of maximum runoffs, while it was in low positive correlation with the peaked tendency of summer maxima. The rather low correlation between precipitation and maximum runoff could be explained in two ways. First, the variation of mean annual precipitation is quite small in Finland and no especially rainy districts exist. Secondly, the high annual precipitation in the Finnish conditions does not necessarily mean heavy rainstorms, which are the basis for summer maximum runoffs. This conclusion can be drawn from the precipitation maps of Finland (Helimäki 1967, Lemmelä and Solantie 1977, Uppala 1978).

The **water equivalent of snow** (W_m, W_h, W_e, W_p) explained spring maximum runoff well, but not better than the altitude did. The influence of the average snowpack clearly decreased when moving from the daily mean maximum to the instantaneous and exceptional maximum runoff. There was no difference, practically speaking, between the various snowpack indices; therefore the average water equivalent of snow in 15 March, taken from the map, was mostly used. The water equivalent of snow also correlated with the summer maximum runoff (MHq_s) being in a way a general index for a northern location, high altitudes, a low percentage of cultivated land, and a moderate or high percentage of coarse soils.

The water equivalent of snow decreased the ratio of exceptional and average spring maximum runoffs, being in good agreement with an earlier study (Seuna 1977a), which stated that the statistical distribution of snow cover for different years is much more uneven in southern and western Finland than in eastern and northern parts of the country. On the contrary, snow cover did not affect the peaked tendency of runoff, which can also be concluded from an earlier study (Mustonen 1965 c).

The **average summer precipitation** (P_s) influenced quite parallelly with the annual precipitation. However, it was in a higher positive correlation with the spring maximum runoff than the annual precipitation. This again stems from low altitudes, high percentage of cultivated land, and vicinity of the coast, all of which are associated with low summer precipitation. The summer precipitation did not markedly affect the extremity or the peaked tendency of maximum runoffs.

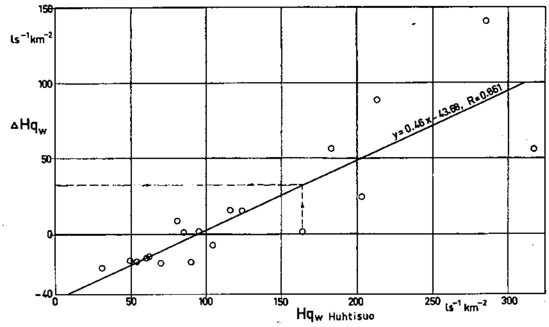

Fig. 17. The method for removing the effect of the magnitude of runoff from the change of runoff in the trend analyses, i.e. the »purification» method. Using the regression equation between Δ q and q, a correction factor (indicated with dashed line) is subtracted from the original change Δ q. A purified trend is the trend of Δ q minus the correction factor.

5. LONG-TERM AND SHORT-TERM EFFECTS OF FORESTRY DRAINAGE ON RUNOFF AND SEDIMENT DISCHARGE

The long-term effects of forestry drainage on the hydrology of an open bog were studied at the Huhtisuo experimental basin, Ruokolahti, in south-eastern Finland. In this study a control basin method was employed (Nos. 43 and 44, Fig. 1). The changes in annual, monthly, spring and summer maximum together with winter and summer minimum runoff were investigated (Mustonen and Seuna 1971 a, b, Seuna 1980, Seuna 1982 a).

The short-term changes in runoff and in sediment discharge caused by forestry drainage were studied at the Ylijoki experimental basin, Ranua, in northern Finland. A control basin method was also employed in this study. The investigation was discussed in more detail by Seuna (1982 b).

5.1 Hydrological changes in the Huhtisuo basin

5.11 Method

In this study a control basin method and trend analysis were employed. In the control basin method the research basins are kept in their natural state during a calibration period. Following calibration the experimental basin is altered in accordance with the purpose of the study (i. e. drained) and the other basin is kept in its natural state as a control basin throughout the study period. Regression equations are computed for the desired runoff quantities of the treatment and control basins for the calibration period. These equations are utilised, following treatment, in order to calculate what the runoff would have been if draining had not been performed. The difference between the calculated and observed runoffs indicates the change caused by draining, providing no other treatment has been employed. In this study the statistical significance of the change was determined using the analysis of covariance and the F-test (Kovner and Evans 1954).

Trend analyses were carried out for the runoff during the post-drainage period 1961—1979. This was carried out employing mostly purified runoff changes. Purification was needed for two reasons. First, the change in runoff depended on its magnitude. Secondly, there was also a decreasing 'trend' in runoff of the control basin throughout the observation period due to climatological variation. The purification was performed by correlating the computed runoff changes of each year with the observed runoff of the treatment basin. The correction factor given by this regression line was subtracted from the original change in order to obtain the pure effect of time.

The purification method is illustrated in Fig. 17.

5.12 Basins and treatments

In 1935, hydrological observations were commenced on the two adjacent basins, Huhtisuo and Latosuo in south-eastern Finland. The purpose of these observations was to calculate, with the aid of comparison, the hydrological changes caused by forestry drainage of the Huhtisuo basin. These basins are in certain respects similar (Table 6).

The control basin (Latosuo) contains pine bogs and spruce swamps comprising 15 per cent of the drainage area, and a large cultivated area (19 per

Table 6. Data on the research basins of Huhtisuo and Latosuo.

Basin	Drainage area km^2	Peatland %	Cultivated land %	Mean slope %	Altitude slope ma.s.l.	Tree stand (m^3 ha^{-1})	
						1958	1970
Huhtisuo	5.03	44	0	5.0	100—125	58	39
Latosuo	5.34	15	19	8.2	80—130	58	74

cent), which was reclaimed long ago from peatland. The experimental basin (Huhtisuo) contained no cultivated areas. Open bogs and bogs with a poor growth of pine comprise about 45 per cent of the basin. Before draining, the peat layer was about 1.5 m thick. The mineral soil below the peat is mostly sand and gravel. The control basin also contains some sandy soils (12 per cent). Both basins are uninhabited.

The climate in the region is humid. Mean annual precipitation is about 700 mm with a range of 500—850 mm. Approximately 270 mm of the total precipitation is discharged and 430 mm evaporates as a long-term average. Much of the precipitation is in the form of snow. The average water equivalent of snow on 15 March is about 120 mm. Thus spring runoff forms a considerable part, about 50 per cent, of the total annual runoff. Precipitation is fairly evenly distributed throughout the year so that most of the rain falls in August, about 80 mm, and least in March, about 40 mm. The mean annual temperature is 4 °C with a range of +1 to +6 °C. The warmest month is July with a mean temperature of 17 °C, and the coldest is February, with a mean temperature of —9 °C.

Draining was carried out in 1958—1960. The main ditches, 130 cm deep, were dug in the Huhtisuo basin in 1958. Draining was completed in 1960 by digging small forest ditches, 60 cm deep. The drainage density was 80 m of main ditch and 225 m of forest ditch per drained hectare. The drained area comprised 40 per cent of the Huhtisuo basin.

In Fig. 18 the same area of the Huhtisuo basin is shown in 1960, 1971 and 1980.

The period 1958—1960 was not studied separately because of its short duration. The treatment period was therefore considered to begin in 1961, while the calibration period extended from 1936 to 1957.

When a control basin method is used both basins must be kept unchanged throughout the research period except for the treatment of the experimental area. In this case this was not quite achieved. Before 1956 changes in the basins were

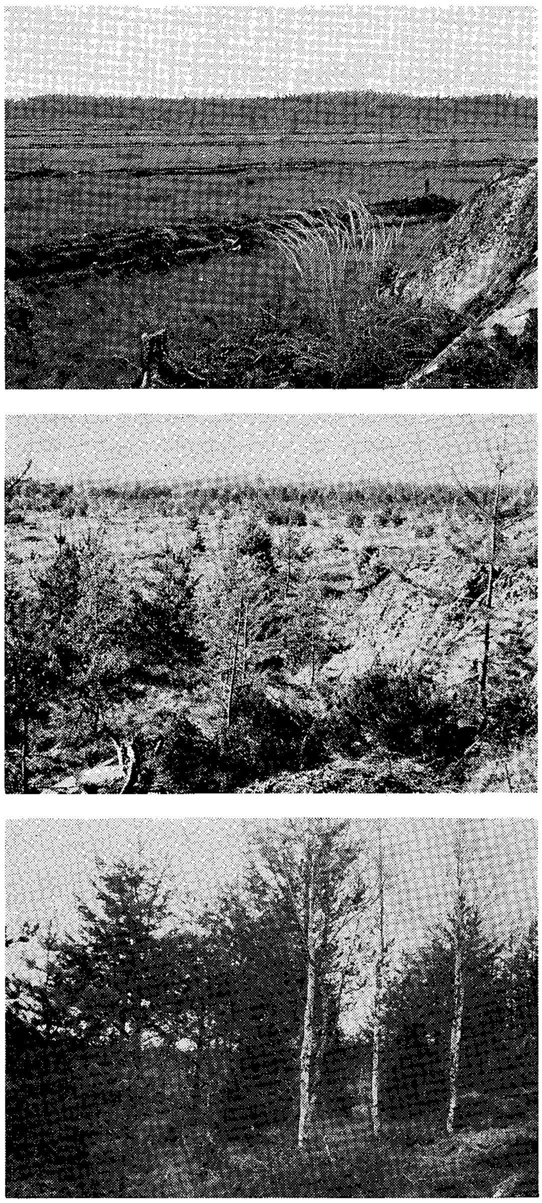

Fig. 18. The same draining area of the Huhtisuo basin in 1960 (above), in 1971 (middle) and in 1980 (below). The forest ditches were dug in 1960.

insignificant. In 1956 some forest draining and clearcutting was carried out in both basins. The drained area in the Huhtisuo basin was four per cent and in Latosuo seven per cent. Clearcutting accounted for 12 and 9 per cent of the two basins, respectively. Both draining and clearcutting increase runoff (Mustonen 1965 c; Mustonen and Seuna 1971a). The percentages justify the conclusion that the effects of these changes are largely eliminated in the computation. For this reason they have not been taken into account in the computations of runoff changes.

During the period 1958—1970 the volume of growing stock increased in the Latosuo basin and decreased in the Huhtisuo basin because of the differences in silvicultural treatment (Table 6). Because of these changes the volumes of growing stock differed by 28 m^3 ha^{-1} during the period 1961—1969, on average. It has been shown (Mustonen 1965 c) that a decrease of 10 m^3 ha^{-1} in growing stock causes an increase of 7.7 mm in annual runoff. On this basis, the average increase in annual runoff was 22 mm in 1961—1969. No tree stand measurements are available after 1970. However, we can assume that there have been no major changes in the volume of growing stock since 1970. On the other hand, the coverage of the tree stand may have increased considerably due to pine plants growing in the peat area of the Huhtisuo basin.

It has not been possible to take the changes in growing stock into account in any runoff quantities other than annual runoff. However, changes in growing stock obviously have an effect on other runoff quantities, due to the changes in melting conditions and interception. For spring maximum runoff this was clearly shown in chapter 4.

The volume of water stored in the soil varies and the observed changes in runoff may be 'too small' or 'too big' for a single year. However, these under or overestimates cannot be corrected due to the lack of soil moisture observations. On the other hand, groundwater level and laboratory tests on the air space of the peat are available, and the settling of the peat surface has also been measured. The total settling during the period 1961—1969 was 120 mm and the increase in the air space of the peat was 50 mm. The total decrease in the water storage of peatland was thus 170 mm. Calculated for the whole basin, for one single year the depletion of the water storage contributed on average 0.40 · 170/9 = 8 mm to the annual runoff. Obviously the annual contribution was considerably greater than 8 mm in the first post-drainage years and somewhat smaller in the last few years.

As with the changes in tree stand, the effects of soil water depletion have been taken into account only in the computation of annual runoff.

5.13 Results

As a result of forestry drainage all runoff quantities increased, especially in the first post-treatment years. The changes of different runoff quantities are discussed in more detail below.

5.131 Annual runoff

Mean annual runoff for the period 1961—1969 increased 3.02 l s^{-1} km^{-2} or 95 mm on average (Fig. 19). This was 43 per cent of the value calculated on the basis of the calibration period and was statistically significant (risk < 0.1 per cent). Of this 95 mm, the depletion of the water storage contributed about 8 mm per year and tree cutting about 22 mm per year, as mentioned earlier. Hence the net increase in runoff due to the decrease in evapotranspiration was 95 — 8 — 22 = 65 mm per year, on average. This is 29 per cent of the mean 'undrained' annual runoff in 1961—1969. The decrease in evapotranspiration is evidently due to the drop in the groundwater table and to the drying of the upper layer of the peatland. Probably transpiration of lower vegetation also decreased due to unfavourable conditions.

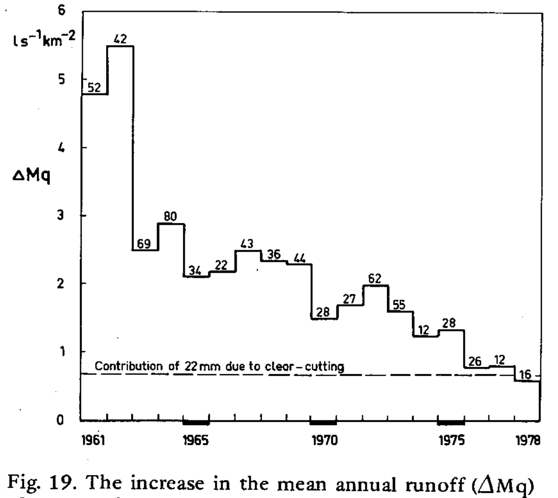

Fig. 19. The increase in the mean annual runoff (ΔMq) after the forestry drainage of the Huhtisuo basin. Figures above the columns indicate the increase in per cent.

The average annual increase in the second half of the post-treatment period (1970—1978) was 1.29 l s^{-1} km^{-2} or 41 mm, which is 18 per cent of the 'undrained' runoff. If the correction factors discussed above are taken into account, the net annual increase in the second half of the period after drainage was around 15 mm, in view of the fact that the depletion factor has decreased further.

The trend analysis was carried out using observed changes without the corrections mentioned above. This can be regarded as justified because it is the trend in changes that is being considered and the constant correction does not affect it. The depletion factor is not constant during the post-treatment period, but as a real contribution caused by drainage it was included in runoff trends.

There was a clear decreasing trend in the influence of drainage (Fig. 20). The unpurified trend could be expressed by a linear regression equation $y = -0.204\,x + 16.4$, $R = -0.856$, where y = annual increase in runoff in l s^{-1} km^{-2}, and x = year — 1900 (e.g.;$x_{1979} = 79$). This trend was statistically significant (risk < 0.1 per cent). The purified trend was statistically significant, too, but at a lower level, risk < 1 per cent. In this case the trend equation was $y = -0.096\,x + 6.66$, $R = -0.629$, when the purification was carried out as earlier explained (Fig. 17).

The runoff after 15—20 years appeared to settle down to the level before drainage, if the contribution caused by clearcutting is taken into account (Fig. 19).

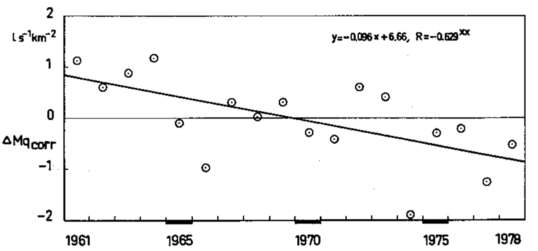

Fig. 20. The purified trend of the mean annual runoff after the drainage of the Huhtisuo basin. $y = \Delta Mq_{corr}$ = the change in runoff corrected for the magnitude of runoff, x = a year minus 1900.

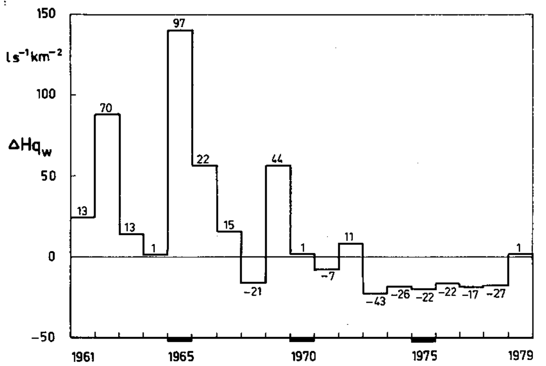

Fig. 21. The change in the spring maximum runoff (ΔHq_w) after the forestry drainage of the Huhtisuo basin. Figures at the top of the columns indicate the change in per cent.

5.132 Maximum runoff

Both spring and summer maximum runoff increased clearly in the first post-drainage years as a result of draining (Figs. 21 and 22). In 1961—1969 spring maximum runoff increased by 42 l s^{-1} km^{-2} or 31 per cent, and the summer maximum by 49 l s^{-1} km^{-2} or 131 per cent, on average, as compared with 'undrained' runoff. The increases were statistically significant at the < 1 and 0.1 per cent risk, respectively. The increases in maximum runoffs were largely due to the accelerating effect of the ditches on the flow. The flood lakes that normally formed on natural peatlands of the Huhtisuo type also disappeared and their levelling effect on runoff was eliminated. The increase in infiltration caused by drying of the surface layer of the peatland was rather slight. During heavy summer rains in particular, the moisture deficit of the peat was rapidly satisfied and the runoff peak was not markedly reduced by increased in-

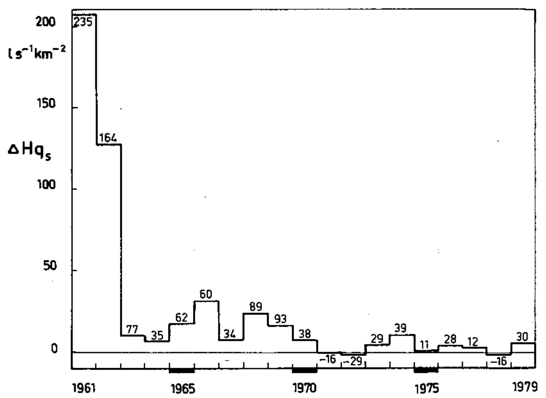

Fig. 22. The change in the summer maximum runoff (ΔHq_s) after the forestry drainage of the Huhtisuo basin. Figures at the top of the columns indicate the change in per cent.

filtration. Thus the runoff caused by heavy rains increased most, in relative terms.

There was evidence that after drainage, in 1961—1969, spring runoff came 1.5 days earlier on average than without draining. This may be partly due to clearcutting but partly due to draining also. When a drained area is situated in the upper part of a river basin, it increases the flood peak of the river for the reason mentioned above.

In the second half of the post-treatment period, i.e. 1970—1979, the average change in spring maximum runoff was negative, —11 l s^{-1} km^{-2},or —13 per cent as compared with the calculated runoff. For summer maximum runoff the change in 1970—1979 was still positive, but only 2.7 l s^{-1} km^{-2}, or 19 per cent of the calculated value, on average. This was probably due partly to the fact that flood peaks were in general lower in the second half than in the first half. This was the case with both spring and summer maximum runoff. As stated earlier, the highest peaks increased most and the increases in low peaks were eliminated by storage in the drained upper layer of the peat. The growing tree stand probably had some decreasing effect on runoff by changing snowmelt conditions and by increasing interception. The third reason could be impairment of the ditches. The conveyance of the ditches was undoubtedly reduced causing a drop in the flood peaks. For these reasons drainage and its co-effects could even reduce small peaks at later stages (Figs. 21 and 22).

When an unpurified trend was calculated for spring maximum runoff, the regression formula was y = —4.60 x + 336, R = —0.599, where y = change in spring maximum runoff (l s^{-1} km^{-2}) and x = year — 1900. The trend was statistically significant at the < 1 per cent risk. However, because of the uneven distribution of high and low peaks during the post-treatment period the uncorrected trend cannot be considered reliable in this case. The purified trend was very weak, y = —0.47x + 33, R = —0.117, and had no statistical significance.

For summer maximum runoff the unpurified trend was statistically significant at the < 1 per cent risk (y = —5.55 x + 413, R = —0.595), but again the data were unevenly distributed throughout the whole period. No purified trend of statistical significance was noticed in this case either (y = 0.12 x — 8.66, R = 0.120).

To summarize the findings concerning maximum runoff, no indisputable trends can be presented due to the lack of high peaks in the latter part of the post-treatment period, although a decreasing trend would be quite logical. On the other hand draining apparently did not increase low peaks after the depletion of the water storage of peatland.

5.133 Minimum runoff

The minimum runoff for both winter and summer increased markedly (Figs. 23 and 24). The increase in both cases was statistically significant at the < 0.1 per cent risk in 1961—1969. Draining made the Huhtisuo basin somewhat similar to the control basin in terms of minimum runoff. This was largely due to the fact that the ditches made flow possible throughout all the seasons of the year. The

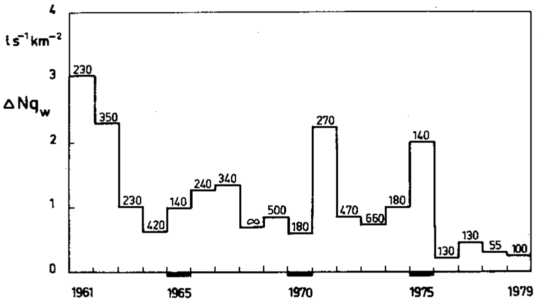

Fig. 23. The increase in the 30-day winter minimum runoff (Δ Nq_w) after the forestry drainage of the Huhtisuo basin. Figures above the columns indicate the change in per cent.

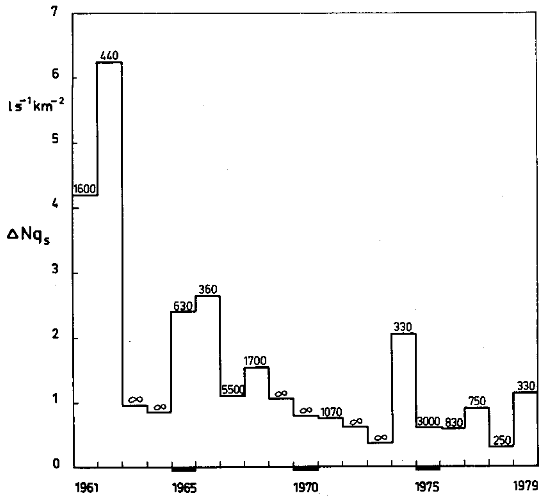

Fig. 24. The increase in the 30-day summer minimum runoff (ΔNq_s) after the forestry drainage of the Huhtisuo basin. Figures above the columns indicate the change in per cent.

main ditches reached the pervious mineral soil, which acted as underground drainage and intensified the effect of drains. Before draining there was only a short, shallow, natural channel in the lower part of the Huhtisuo basin.

Both winter and summer minimum runoffs decreased during the post-treatment period to some extent. For the 30-day winter minimum runoff the purified trend was $y = -0.016\,x + 1.09$, $R = -0.527$, where y and x are as explained earlier. This trend was statistically significant at the < 1 per cent risk.

The purified trend for the 30-day summer minimum runoff was $y = -0.014\,x + 0.96$, $R = -0.512$. This trend was statistically significant at about 1 per cent risk.

The decreasing trend was quite logical, especially for summer minimum runoff, considering the increase in evapotranspiration due to the growing tree stand. However, at the end of the post-treatment period minimum runoffs for both winter and summer still exceeded the 'undrained' values. For summer minimum runoff one must keep in mind the clearcutting mentioned earlier, which may raise the level of runoff changes during the post-drainage period as shown in Fig. 19 for mean annual runoff.

5.14 Discussion

Forestry drainage of the Huhtisuo open bog resulted in considerable increases in all the hydrological quantities studied. As could be expected the effects were greatest during the first post-drainage years. The main reasons for these increases were the depletion of water storage for all runoff quantities, the decrease in evapotranspiration for summer and annual runoff, and the accelerating effect of the ditches on the maximum flows. The decrease in evaporation was obviously resulted from the drop of groundwater table; besides transpiration of lesser vegetation can be expected to have decreased due to unfavourable conditions after drainage. The significant effect of ground water depth on local evapotranspiration has been measured by Virta (1966). For minimum runoff a coarse bottom soil apparently had a considerable effect on the runoff increase.

The effects of drainage notably decreased with time, assumably due to an increase in evapotranspiration after the growth and the recovery of pine plants and lesser vegetation. The decreasing effect was evidently contributed by the impairment of the ditches and by the decrease in water storage.

The pre-drainage level was reached in 15 to 20 years, approximately. In later stages runoff peaks could be even reduced compared with the pre-drainage level, due to the increased storage capacity in peat and due to the changes in snowmelt conditions because of the tree stand.

5.2 Changes in runoff and sediment discharge of the Ylijoki basin

5.21 Methods and measurements

In the late winter of 1976 a control basin study was begun, on two adjacent areas at Ranua, in northern Finland (Nos. 119 and 120, Fig. 1). Runoff was continuously measured using measuring weirs, and various water quality parameters were analysed from the water samples. The water samples were mainly taken by the local observer. Analysis of the water samples taken were carried out at the laboratory of the Civil Engineering Department of the Oulu University for the period 1976 to June 1980 and thereafter at the Lapland Water District's office. Samples have been taken at a rate of 15 to 20 samples a year employing a USDH-48 hand-sampler with vertical integration; the most frequent sampling being taken during the spring floods. The amount of sediment was measured as suspended solids, retained on filter paper (Whatman GF/C 1 μm). The dissolved solids, passed through the filter, were thus not included in the results, nor the bed load. The amount of dissolved solids may be notably high; this conclusion can be drawn from some total residues and high colour values, which are available.

With regard to the bed load some conclusions may be drawn from earlier studies made and from grain size distribution of the soil (e.g. Kalinske 1947, Einstein 1950, Nilsson 1971, Stelczer 1981). The grain size of 0.2 mm, which is typical for drainage area, presupposes about 15 cm s^{-1} for the critical mean velocity of the current (Stelczer 1981). This velocity is normally exceeded in the Ylijoki river. Thus bed load transport can occur, if the appropriate materials are available in the river. After the drainage such material probably exists, but so far no reliable equipment to measure the amount of bed load are available (e.g. Toebes and Ouryvaev 1970, Painter 1979). A rough estimate of 10—15 per cent of the suspended solids has been presented for the bed load of some Swedish rivers (Nilsson 1971).

Fig. 25. The draining area of Kettumaa in the Ylijoki basin in May 1980. The drainage was carried out in the preceding winter.

5.22 Basins and treatments

The treatment basin, Ylijoki and the control basin, Kotioja, are 56.3 km^2 and 18.1 km^2, respectively. The basins are fairly similar as to their physiographic properties, although more bog and peat areas are found in the Ylijoki basin than in Kotioja. The growing stock is rather poor in both basins, but due to the different proportions of bogs, poorer in the Ylijoki basin. The conditions of land slope and soil types are quite similar, even if the Ylijoki area slopes somewhat more to the west and south, the Kotioja area to the east and north. The proportion of peatlands is 64 per cent in the Ylijoki basin and 53 per cent in the Kotioja basin with approximately half of the peatlands having a peat layer less than one meter in thickness. The mineral soil is for the most part coarse sandy moraine, but fine sandy moraine and graded coarse sand occur notably as well. Sands and sandy moraines comprise 30 per cent of the Ylijoki and 36 per cent of the Kotioja basins.

Ditching was started in the Ylijoki basin in the winter of 1978—1979. By the end of October 1979, 5.09 km^2 had been ditched, almost all of it in the upstream parts of the drainage area (Seuna 1982 b). A view from a draining area of the Ylijoki basin is shown in Fig. 25. At the end of 1979 ditching of the downstream parts was begun and this continued until the later part of 1980. A total of 9.60 km^2 or 17 per cent of the catchment area were drained. For the most part, ditches were dug every 30 meters, but single ditches were also dug. The single ditches were considered to drain a strip some 70 meters in width, whereas inside a network of ditches somewhat broader area was included in the drained area. The ditches reached the mineral soil below the thin peat almost everywhere. The draining was continued in 1981 to a lesser extent.

The calibration period was extended until the end of October 1979 for several reasons. The end of October is a natural limit indicating the end of the hydrological year in Finland. However, by the end of 1978 and still before the spring flood of 1979, the drained area did not amount to more than 1.25 km^2. Furthermore, it was located in the very upstream parts of the Ylijoki basin. For these reasons the end of 1978 or the beginning of 1979 could not be used as the end of calibration.

Fairly comprehensive drainings were carried out in the Ylijoki basin also before 1976, mainly in the 1960's. The drained area had increased from 0.42

km^2 in 1963 to 7.04 km^2 or 12.5 per cent in 1975. The effects of these drainings can be considered stable by the beginning of the research. This was supported by the close relationships of runoff and sediment yield between Ylijoki and Kotioja in the calibration period.

In the Kotioja basin old drainings, dug before 1963, amounted to 4.53 km^2. From 1963 to 1975, a small area of 0.27 km^2 had been drained. In the beginning of the study the total drained area thus amounted to 4.80 km^2 or 26.5 per cent of the drainage area. During the investigation period no drainings had been carried out in the Kotioja basin.

In the Ylijoki basin ploughing of the mineral soil intended for forest renewal had been carried out in addition to ditching and it can be concluded that this would influence the runoff in much the same way as forestry draining. But as the ploughed furrows do not form a network of ditches emptying into the water course in the same way as ditches, the ploughing would probably cause less effect than the draining.

This should be borne in mind when considering the results below as no specific mention of the influence of the ploughing is referred to.

5.23 Changes in runoff

The period of observations is clearly too short to permit a detailed study of the changes in runoff, but some preliminary conclusions may be drawn.

The annual runoff increased somewhat (Fig. 26). A small increase was apparent in 1979, as a consequence of the drainage in the headwater area of the Ylijoki basin. The annual increases were 0.9 $l\ s^{-1}\ km^{-2}$ or 8 per cent in 1979, 1.3 $l\ s^{-1}\ km^{-2}$ or 14 per cent in 1980 and 1.5 $l\ s^{-1}\ km^{-2}$ or 9 per cent in 1981.

The spring maximum runoff showed a slight decrease, in spite of the scatter. The reduction could be of the order of 30 to 35 $l\ s^{-1}\ km^{-2}$ or 10 per cent.

The summer maximum runoff is difficult to assess due to low peaks before ditching. If the linear relationship is considered to hold for high summer maxima as well, the drainage increased the summer peaks of Ylijoki by about 40 $l\ s^{-1}\ km^{-2}$ or 35 per cent.

Of the hydrological changes those of minimum runoffs have been strongest. The average increase in a 30-day winter minimum has been about 0.65 $l\ s^{-1}\ km^{-2}$ or over 50 per cent of the "undrained"

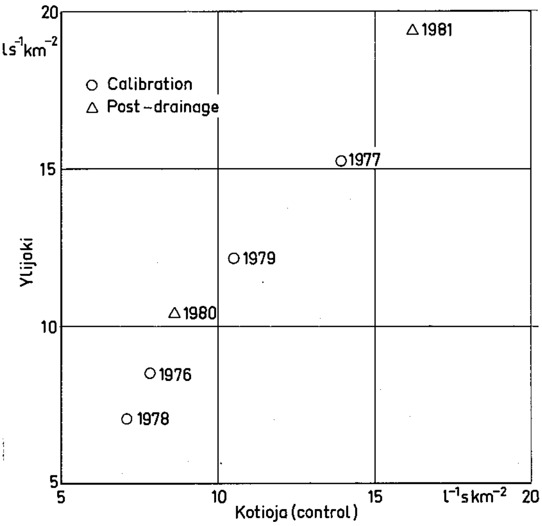

Fig. 26. The relationship between the mean annual runoff of the Ylijoki and the Kotioja basins in 1976 to 1979 (circles) and in 1980 to 1981 (triangles).

value in 1980—1981. This change is also statistically significant (risk about 1 per cent).

The points for the summer minima are scattered, but the 30-day summer minima for 1980 and 1981 are higher than those for the calibration period. Here, too, one may assess the increase at several tens of per cents, which is not, however, statistically significant.

The changes in runoff seem to have partly occurred as early as in 1979, when the draining in 1978 in the upper parts of the Ylijoki basin began to take effect.

5.24 Changes in sediment transport

To compute the sediment transport, the data was divided into the following classes

class 1 = summer, increasing runoff
class 2 = summer, decreasing runoff
class 3 = winter, increasing runoff
class 4 = winter, decreasing runoff
class 5 = spring, increasing runoff (>5 $l\ s^{-1}\ km^{-2}$) with the ground frozen
class 6 = spring, decreasing runoff (> 5 $l\ s^{-1}\ km^{-2}$) with the ground frozen
class 7 = spring, increasing runoff (> 10 $l\ s^{-1}\ km^{-2}$) with the ground thawed
class 8 = spring, decreasing runoff (> 10 $l\ s^{-1}\ km^{-2}$) with the ground thawed

5.241 Concentration of suspended solids before draining

The natural mean concentrations of suspended solids before draining were in the Kotioja samples 4.1 mg l^{-1} and in the Ylijoki 3.9 mg l^{-1}. The standard deviations were 4.7 and 3.0 mg l^{-1} respectively. In the various groups, the Kotioja value for frozen ground in the spring was larger than in the rest of the material, in the mean 6 to 7 mg l^{-1}. For both areas in the natural state the concentration in summer was lower than in the rest of the material, in the mean 3 to 3.5 mg l^{-1}.

Comparing summer and winter values, the ground being either unfrozen or frozen, there was no difference in the mean in the natural state. The same applies to the mean concentrations of suspended solids, when comparing increasing and decreasing runoff in the natural state. There were somewhat higher concentrations during large runoff in Kotioja, but the concentration in Ylijoki did not increase even at times of a large runoff, before ditching.

The dependence of the concentration of suspended solids on runoff was tested with a common equation $S_s = aq^b$ (e.g. Östrem et al. 1971, Geary 1981) using both the undivided data and the data divided into classes (S_s = concentration of suspended solids in mg l^{-1}, q = runoff in $l\ s^{-1}\ km^{-2}$, a and b coefficients).

The concentration of suspended solids only weakly correlated with the runoff in the Kotioja and the Ylijoki area in the natural state; in the Kotioja data at the < 5 per cent risk, and in the Ylijoki data not at all. In the different classes, the data for Kotioja in spring with a decreasing runoff from frozen soil showed a statistically significant correlation (R = 0.710, risk < 5 per cent). Additionally, increasing runoff of Ylijoki in summer correlated at the < 5 per cent risk with the concentration of suspended solids.

With a division summer-winter, only the summer data for Ylijoki and the winter data for Kotioja showed a weak correlation between concentration and runoff, risk < 5 per cent. When dividing the data in increasing and decreasing runoff the model did not explain the variation of pre-drainage concentration at a significant level, even if the correlation coefficients were logical (positive).

5.242 Concentration of suspended solids after draining

After the draining the concentrations of suspended solids were in the mean 15.1 mg l^{-1} in Ylijoki and 4.4 mg l^{-1} in Kotioja. The concentration of suspended solids in the Kotioja thus has not changed much, whereas the mean concentration in the Ylijoki samples is almost fourfold of that before the ditching. One should note, however, that the samples taken after the ditching represent larger runoffs than concentration of the samples taken earlier. Also the scatter of the concentration data for Ylijoki has increased since ditching, the standard deviation being 19.4 mg l^{-1}. The concentration increased especially for large runoff values. No clear difference was found between summer and winter data; on the other hand, the increase in concentration was most marked for a rising runoff. The ditch-digging in the uppermost part of the Ylijoki basin in 1979 did not notably influence the concentration at the site of the measuring weir.

After the ditching the concentration of suspended solids in Ylijoki depended clearly on runoff. The correlation coefficient 0.727 of the model (36) $S_s = 1.44\ q^{0.52}$ for the total set of data was statistically significant (risk < 0.1 per cent). Significant functions were also the models (37) — (41)

$S_s = 1.87\ q^{0.48}$, R = 0.765, risk < 0.1 per cent, for the winter data (37)
$S_s = 0.86\ q^{0.58}$, R = 0.650, risk < 5 per cent, for summer runoff (38)
$S_s = 1.51\ q^{0.43}$, R = 0.699, risk < 0.1 per cent, for decreasing runoff (39)
$S_s = 1.64\ q^{0.66}$, R = 0.863, risk < 1 per cent, for increasing runoff (40)
$S_s = 5.87\ q^{0.41}$, R = 0.805, risk < 5 per cent, for increasing spring runoff with frozen ground (41)

5.243 Concentration correlations between the basins

Before the ditching, the summer as well as the winter concentration for decreasing runoff showed a significant correlation between the basins, as shown in the following: (Y indicates Ylijoki, K Kotioja)

S_s (Y) = 0.50 S_s (K) + 2.05, R = 0.611, risk < 0.1 per cent, all data (42)
S_s (Y) = 0.53 S_s (K) + 1.81, R = 0.760, risk < 0.1 per cent, decreasing summer runoff (43)
S_s (Y) = 0.90 S_s (K) + 1.42, R = 0.750, risk < 0.1 per cent, decreasing winter runoff (44)

After the drainage the correlations were also low, although part are statistically significant. For all data S_s (Y) = 1.56 S_s (K) + 7.83, R = 0.505, risk < 1 per cent, (45) and for decreasing winter runoff S_s (Y) = 1.00 S_s (K) + 0.80, R = 0.916, risk < 1 per cent, (46).

The control basin method requires a close correlation during the calibration period between the basins. For the concentrations this requirement was not fulfilled sufficiently and changes of concentrations due to the drainage could not be investigated in a normal control basin way.

5.244 Annual load of suspended solids

Two methods were used to compute the annual load of suspended solids. First, the group means of the concentrations for the following classes were used: before the ditching: winter, summer and spring; after the ditching: winter, summer, spring with rising and decreasing runoff during frozen soil, spring with decreasing flow during thawed ground. Secondly, for the period after the ditching the function $S_s = aq^b$ was applied for the spring classes. This concerned class 5, spring with increasing flow during frozen ground, to which was added class 7, spring with increasing flow during thawed ground, and also class 8, spring with decreasing flow, thawed ground. For the runoff, daily mean values were taken, and daily discharge of suspended solids was calculated.

Dividing the year into parts as above, the data presented in Table 7 were obtained.

The annual load in Ylijoki correlated from 1976 to 1979 well with that of Kotioja (Fig. 27). The linear regression equation was

$$S_s\,(Y) = 1.022\ \ S_s\,(K) - 0.033, \qquad R = 0.981, \qquad \text{risk} < 0.1 \text{ per cent} \qquad (47)$$

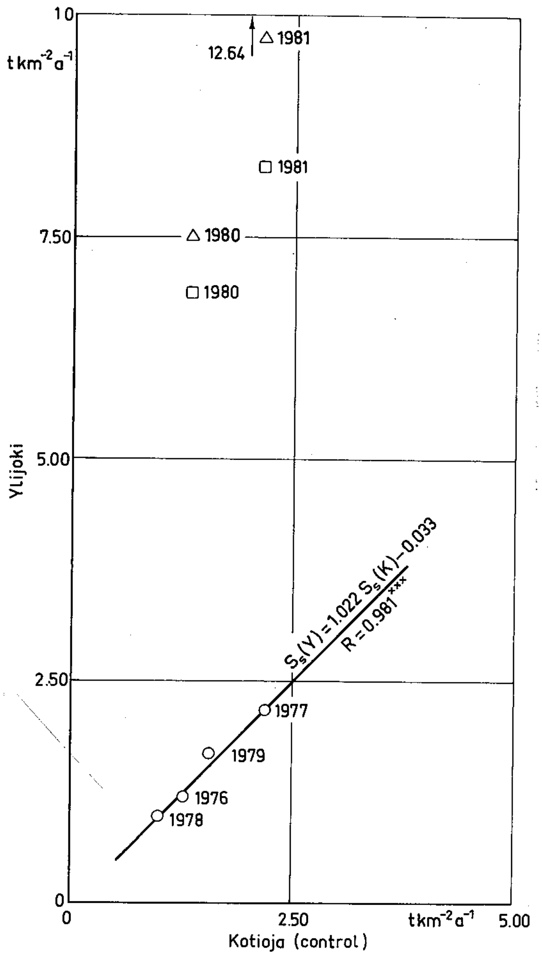

Fig. 27. The annual yields of suspended solids of the Ylijoki and the Kotioja basins in 1976 to 1979 (circles) and in 1980 to 1981 (triangles). Squares indicate the yield calculated using group means.

Table 7. Transport of suspended solids (t km^{-2}) in Ylijoki (Y) and Kotioja (K) from 1976 to 1981. The transport has been calculated using class mean values, except for the spring values of Ylijoki after ditching, which were obtained using the function of concentration vs. runoff.

Year	1 Jan.—spring		Spring		Summer		1 Nov.—31 Dec.		The whole year	
	Y	K	Y	K	Y	K	Y	K	Y	K
1976	0.07	0.07	0.93	1.02	0.14	0.13	0.05	0.05	1.20	1.27
1977	0.06	0.05	1.53	1.62	0.39	0.36	0.18	0.17	2.17	2.20
1978	0.06	0.05	0.52	0.63	0.38	0.32	0.03	0.03	0.99	1.03
1979	0.02	0.01	0.96	0.99	0.62	0.45	0.09	0.08	1.68	1.53
1980	0.07	0.05	7.06 1)	1.04	0.32	0.22	0.03	0.02	7.49 2)	1.33
1981	0.06	0.04	11.31 3)	1.26	1.17	0.78	0.10	0.09	12.64 4)	2.16

1) When using class mean values 6.45
2) When using class mean values 6.87
3) When using class mean values 6.97
4) When using class mean values 8.30

If this regression equation is used to compute, what the load in Ylijoki had been in 1980 and 1981, if no ditching had been carried out, the following increases caused by drainage are obtained:

1980 6.16 t km^{-2} or 465 per cent of the "undrained"
1981 10.48 t km^{-2} or 483 per cent of the "undrained"

The increase of the annual load of suspended solids after the ditching to 5 or 6 times that computed for the natural state is statistically significant (risk < 0.1 per cent) irrespective of the short period studied. If the annual loads are computed using only the class mean values of the concentrations, the increase of load in Ylijoki is 5.54 t km^{-2} or 414 per cent in 1980 and 6.17 t km^{-2} or 283 per cent in 1981. These values as well are statistically significant (risk < 0.1 per cent). But this method flattens out the peaks to such an extent, that one should expect the larger values (465 and 483 per cent) to be more correct.

This increase in the load of suspended solids falls almost altogether on the maximum spring runoff (Table 7). Only during the unusually rainy summer of 1981 did the transport of suspended solids increase somewhat in summertime also. Generally speaking, the spring is dominating in determining the annual load of suspended solids. Before the ditching, the spring transport made up 65 per cent of the annual transport in Ylijoki and 68 per cent in Kotioja, on average. After the ditching the spring part became still larger in Ylijoki, 91 per cent in the mean. At the same time, the spring transport in the Kotioja was 59 per cent of the annual load.

In Figures 28 and 29 the discharge of suspended solids and runoff of Ylijoki are shown for 1976 and 1980. The strong peaked tendency of sediment transport during big runoff is clear in 1980, even though it is still clearer in daily values. The largest daily values of sediment transport were computed to be almost 1000 kg km^{-2} d^{-1}.

As a separate experiment transport from a very ditching area, Kettumaa, was measured. The Ket-

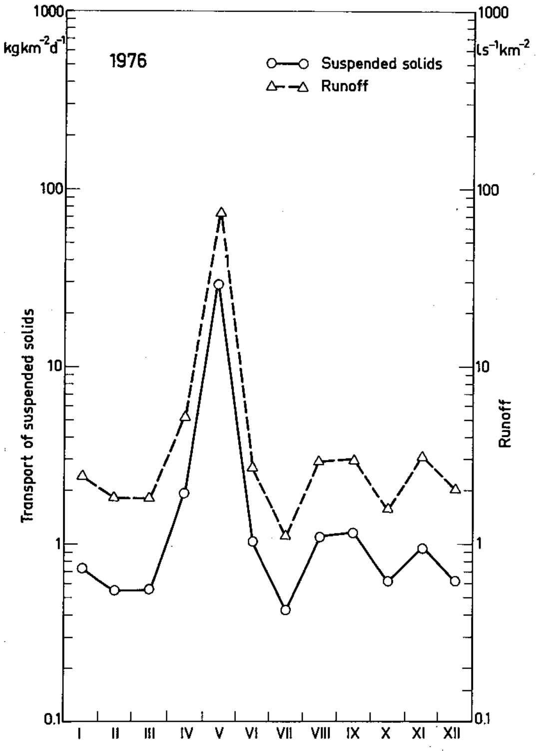

Fig. 28. Discharge of suspended solids (solid line and the left-hand scale) and runoff (dashed line and the right-hand scale) of the Ylijoki basin before forestry drainage in 1976.

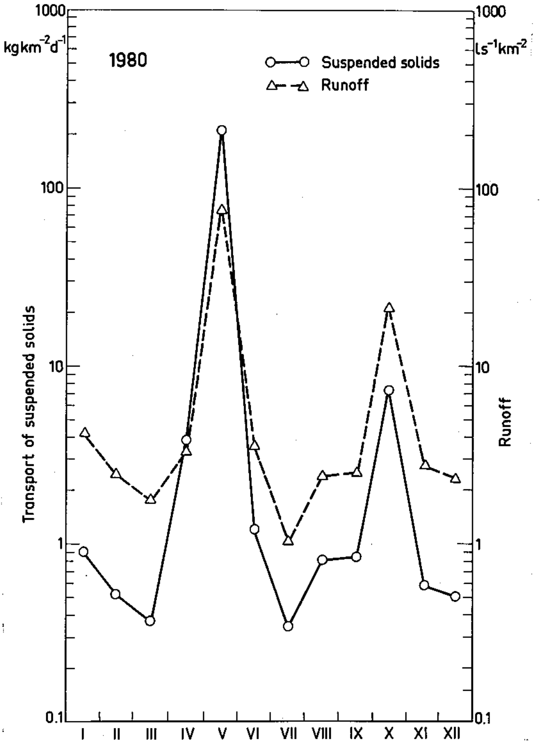

Fig. 29. Discharge of suspended solids (solid line and the left-hand scale) and runoff (dashed line and the right-hand scale) of the Ylijoki basin after forestry drainage in 1980.

tumaa ditching area was 12 ha, and the draining was carried out in December 1979. In the spring of 1980 the concentrations of suspended solids from this area were exceptionally high; generally several hundreds of milligrams per litre and maximally 2000 mg l^{-1}. The concentration increased with the rising hydrograph and began to decrease somewhat more rapidly than runoff. When the soil frost melted a very rapid and strong rise in concentration occurred, although runoff continued to decrease. This concentration peak was even higher than the one during the flood peak. The same was observed during the spring of 1981, although at a much lower level. The total discharge of suspended solids during the spring flood of 1980 was about 230 t km^{-2} from that particular ditching area. The highest daily values were over 30 t $km^{-2} d^{-1}$. In this case the ditches reached the mineral soil, which was fine sand moraine comprising about a half of the fraction 0.06—0.6 mm diameter.

5.25 Discussion

In this study the forestry drainage of about 17 per cent of area did not cause dramatic changes in runoff, even if some differences from the natural state were evident. On the contrary, the transport of suspended solids increased strongly, relatively speaking. Even if the annual loads still remain low on a global scale, they may have disadvantageous consequences in the oligotrophic waters of Finland. This could be supported by the fact that many of the water quality characteristics are closely associated with suspended solids (Walling and Webb 1982).

On the other hand, the transport of sediments involves a serious problem as far as measurement is concerned, both temporarily and spatially. Considering the big variation of the concentrations a frequent sampling program would be needed especially during flood periods. However, practical availabilities usually cause restrictions in this respect. Spatially, only the load passing the observation point can be discussed. This may not necessarily equal to the load in another site of the same river or give a general picture of the sediment discharge from the catchment, due to varying erosion — deposition relations along the channel.

As far as the duration of the changes caused by the drainage is concerned, a two-year post-treatment period is too short a period to determine an accurate clarification. However, it can be concluded that the drainages performed in the 1960's did not continue to have an effect after 1976, as the calibration equations were close and stable. In addition to this the concentrations of the Ylijoki and the Kotioja basins were almost equal during the calibration period.

6. INFLUENCE OF SUB-DRAINAGE ON WATER QUANTITY IN A CULTIVATED AREA IN FINLAND

6.1 Methods and measurements

An investigation to study the effects of sub-drainage was started in 1953, when measuring weirs were built and various hydrological observations were begun in two adjacent basins at Vihti, in southern Finland. A control basin method and trend analysis were used (Seuna and Kauppi 1982).

Water quality observations were started in 1966, however, in this context, only hydrological changes are discussed.

6.2 Basins and treatments

In Table 8 some physiographic characteristics are given.

The experimental basin, Hovi, was entirely open-ditched cultivated land, while the control basin, Ali-Knuutila, was composed of 48 per cent open-ditched cultivated land and 42 per cent forest.

Table 8. Physiographic characteristics of the research basins (Mustonen 1963).

Basin	Area	Cultivated land	Forest	Building site, pasture, road	Mean slope	Drainage density
	ha	%	%	%	%	m ha^{-1}
Hovi	12.0	100	0	0	2.8	920
Ali-Knuutila	24.6	48	42	10	10.0[1)]	454[2)]

1) Cultivated land 3.9 per cent, forest 16.0 per cent.
2) Cultivated land 950 m ha^{-1} of open ditch, forest unditched

Table 9. Precipitation (mm) and air temperature (°C) at the research basins.

	1953—1970		1972—1979	
	Range	Mean	Range	Mean
Mean annual air temperature	2.2 to 5.5	3.7	2.5 to 5.8	4.1
Annual precipitation	448 to 836	626	467 to 701	573
Mean February temperature	—0.9 to —15.2	—9.1	—0.3 to —13.2	—7.0
Mean July temperature	13.7 to 17.4	15.9	14.3 to 19.3	16.2

The growing stock in the forest area of the Ali-Knuutila basin was 114 m^3 ha^{-1} corresponding to the regional mean. The soil at the Hovi basin is for a notable part heavy clay, 55 per cent of area. Heavy clay dominates in the cultivated part of the Ali-Knuutila basin as well, 23 per cent of total area. In the forest area of the Ali-Knuutila basin sand moraine prevails, 27 per cent of total area.

A climatic station is located about 2 km from the research plots. Measurements of snow cover and soil frost were performed on the research basins.

As shown above there are differences between the experimental (Hovi) and control (Ali-Knuutila) basins. The cultivated areas of the basins were originally of much the same nature, but the forest area of the control basin causes certain differences. These do not, however, create serious disadvantages, as can be confirmed by the fairly close correlations found between the runoff quantities of the experimental and control basins during the calibration period.

In 1971 the Hovi basin was sub-drained. Drainage density was 443 m ha^{-1} and drainage was carried out using 55 mm plastic tubes as lateral drains and 100 mm steel and plastic tubes as main drains. By building low embankments the watershed was kept unchanged. This was repeated every autumn in connection with ploughing. After sub-drainage surface runoff and runoff from the sub-drains could be measured separately by weirs.

The calibration period was in general 1953—1970 for water quantity parameters and the treatment period mostly 1972—1979.

Climatic conditions varied considerably in both periods (Table 9). The treatment period was on average slightly warmer and drier than the calibration period but these differences were not statistically significant.

6.3 Influence of sub-drainage on runoff

6.31 Distribution of runoff

After drainage, surface runoff decreased considerably. Of the total annual runoff 77 per cent came from sub-drains and only 23 per cent from surface runoff, on average, in 1972—78. During the snowmelt period (1 March—31 May) 59 per cent of the total runoff came from sub-drains, on average. Runoff from sub-drains averaged 56 per cent of the total spring maximum runoff and 98 per cent of the summer maximum runoff, although the soil is very clayey. During the instantaneous maximum the runoff from sub-drains averaged 38 per cent in spring and 97 per cent in summer of the total instantaneous maximum.

The instantaneous spring maximum runoff (total) of the treatment basin was 110 per cent higher than the average daily maximum for the calibration period. For the post-treatment period this figure was 120 per cent. For summer the percentages were 225 per cent and 130 per cent, respectively.

During springs with deep soil frost (1972, 1976, 1978 and 1979) the percentage of surface runoff was greater than the average, as would be expected. The structure of soil frost obviously had an effect on the distribution of runoff. In the years 1973 and 1975, when the upper layer of soil frost had already melted until the spring maximum runoff, the percentage of surface runoff was extremely small, although the total depth of the soil frost was still considerable (Fig. 30). The relationship between runoff from sub-drains R_s ($l\ s^{-1}\ km^{-2}$) and frost depth F_d (cm) was $R_s = —2.01\ F_d + 170$, $R = —0.857$. This means that with no soil frost, spring maximum runoff from sub-drains in this area would be about 170 $l\ s^{-1}\ km^{-2}$, which in fact is near to the normal design value for sub-drains used in Finland. In summertime, practically no surface runoff has been measured after the sub-drainage. Even during the heaviest rains almost all runoff has discharged through the sub-drains (Fig. 31). It seems evident that the permeability of soil decreased to some extent during the post-treatment period especially at the sites of the sub-drains. This was reflected in the increase in the percentage of surface runoff during the recent years, especially in the case of spring runoff. This trend, although a little mixed

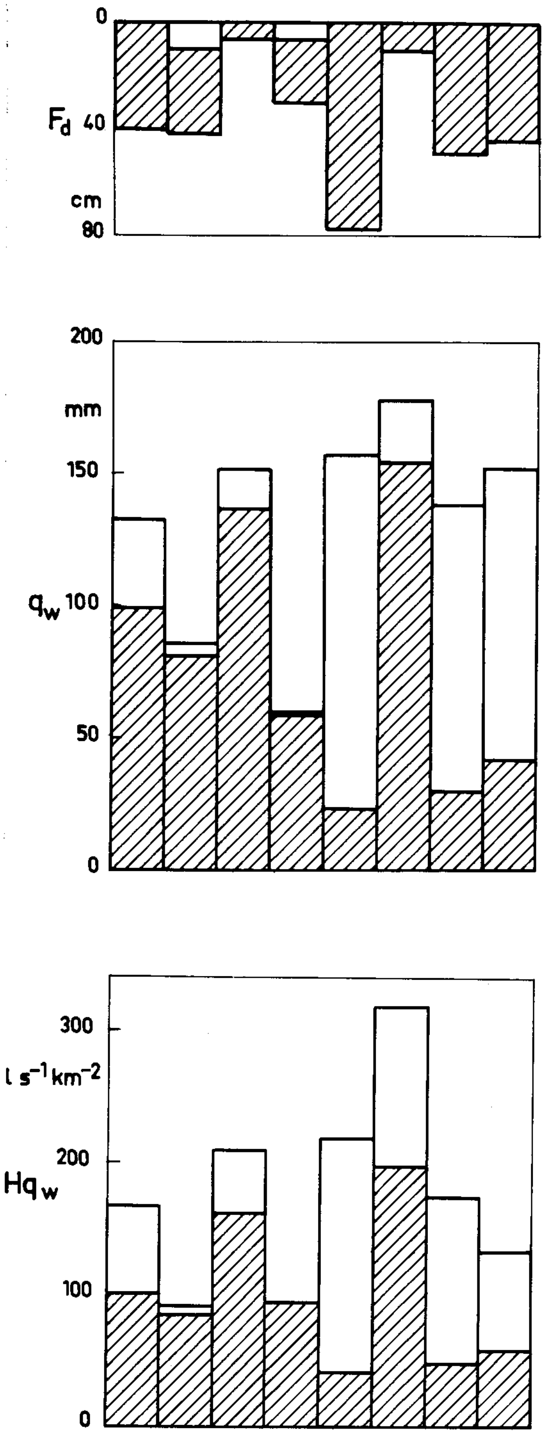

Fig. 30. Spring runoff (q_w) and spring maximum runoff (Hq_w) from sub-drains (hatched) and surface (unhatched) of the Hovi basin after sub-drainage. F_d indicates the depth of soil frost during the spring maximum runoff.

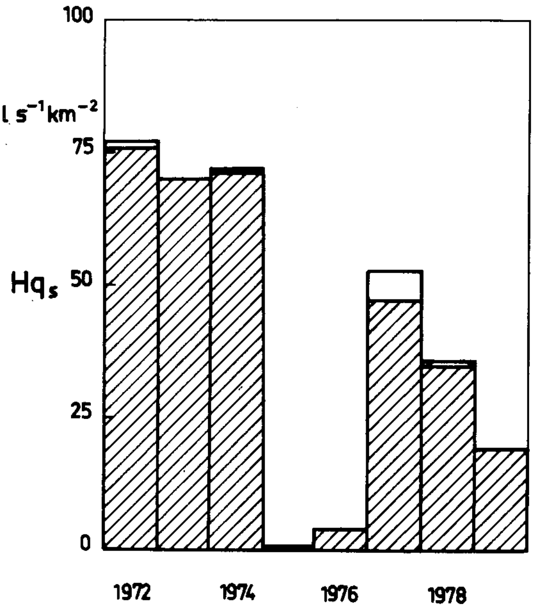

Fig. 31. Summer maximum runoff (Hq_s) from sub-drains (hatched) and surface (unhatched) in the Hovi basin after sub-drainage.

with the effect of frost depth variation, may be expected to continue in the future.

6.32 Increase or decrease in runoff

Runoff changes caused by sub-drainage were computed for mean annual (Mq), snowmelt (q_w), spring maximum (Hq_w), summer maximum (Hq_s), 30-day winter minimum (Nq_w) and 30-day summer minimum (Nq_s) runoff. In this connection values of total runoff, i.e. the sum of runoff from sub-drains and surface runoff were used. Regression equations for the calibration (1953—1970) and treatment (1972—1979) periods were as follows (treatment basin = y; control basin = x):

Mq (1 Jan.— 31 Dec.)	1953—1970	$y = 0.95x + 0.08$
	$R = 0.921$	
	1972—1978	$y = 0.95x + 1.02$
	$R = 0.937$	
Mq_h (1 Nov.— 31 Oct.)	1954—1970	$y = 1.00x - 0.31$
	$R = 0.934$	
	1972—1978	$y = 0.84x + 1.66$
	$R = 0.918$	

q_w (1 Mar.— 31 May)	1953—1971	$y = 0.93x + 12.2$
	$R = 0.902$	
	1972—1979	$y = 0.84x + 36.5$
	$R = 0.775$	
Hq_w	1953—1971	$y = 0.93x + 83.7$
	$R = 0.855$	
	1972—1979	$y = 0.90x + 77.3$
	$R = 0.445$	
Hq_s	1953—1970	$y = 1.35x — 13.2$
	$R = 0.975$	
	1972—1979	$y = 0.45x + 17.4$
	$R = 0.832$	
Nq_w	1954—1971	$y = 0.10x + 0.04$
	$R = 0.754$	
	1972—1979	$y = 0.27x + 0.10$
	$R = 0.877$	
Nq_s	1953—1970	$y = 0.19x + 0.01$
	$R = 0.936$	
	1972—1979	$y = 0.48x + 0.05$
	$R = 0.318$	

Mean total annual runoff increased on average 0.91 l s^{-1} km^{-2} or 15.1 per cent for the calender year and 1.06 l s^{-1} km^{-2} or 18.2 per cent for the hydrological year (1 November — 31 October) (Fig. 32). The increase was statistically significant at the < 5 per cent risk. Annual runoff for the hydrological year was increased in all years. There was a slightly rising trend in the increase, which was not, however, statistically significant. The increase in annual runoff can be explained in two ways. First, evapotranspiration and especially evaporation probably decreased after sub-drainage. Secondly, the infiltrated water was mostly drained through the sub-drains and did not percolate to the passive groundwater layer.

Spring runoff (1.3.—31.5.) increased on average 14.6 mm or 12.4 per cent as compared with the calculated 'undrained' value. This increase was not statistically significant and no trend could be found. Although the increase was especially high in 1976, when soil frost was deepest during the post-treatment period, in the other springs with deep frost the increase was not remarkable.

Spring maximum runoff (daily maximum caused by snowmelt) decreased to some extent due to sub-drainage. The average decrease was 9 l s^{-1} km^{-2} or 4.3 per cent. This decrease was not statistically significant. The trend appeared to be rising except for 1979; however, the purified trend was not statistically significant. During the winter of 1979 an ice layer had formed on the depression in front of the embankment, which formed an artificial water divide. Due to the ice, some surface runoff flowed out from the basin. However, the amount

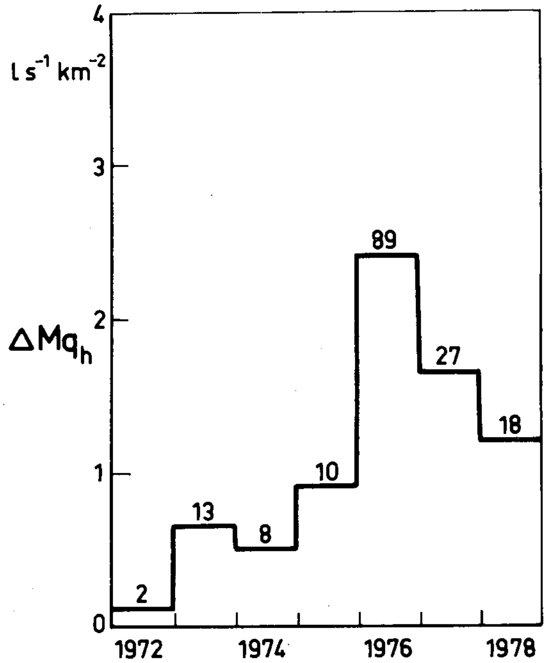

Fig. 32. The change in mean annual runoff of the hydrological year caused by sub-drainage in the Hovi basin. The figures at the top of the columns indicate the percentage of the change.

was not significant according to the survey performed.

The instantaneous spring maximum runoff decreased 8 l s^{-1} km^{-2} or 2 per cent on average due to sub-drainage. The decrease was not statistically significant. No trend on the post-treatment period was observed.

Summer maximum runoff (daily maximum between 1 June and 31 October) decreased 27 l s^{-1} km^{-2} or 36 per cent on average due to sub-drainage (Fig. 33). This decrease was not quite statistically significant, although it was very clear in the first years after sub-drainage. Some years after sub-drainage no remarkable influence could be found on the summer maximum runoff. During the post-treatment period there was a rising trend in runoff change, which was evidently due to the packing of soil in the sites of sub-drains. The unpurified trend was statistically significant at the < 5 per cent risk. The purified trend could not be used because of the low correlation in the purification method mentioned above.

The instantaneous summer maximum runoff decreased 271 l s^{-1} km^{-2} or 74 per cent on average due to sub-drainage. The decrease was statistically significant at the < 1 per cent risk. On the post-treatment period a rising trend appeared at the

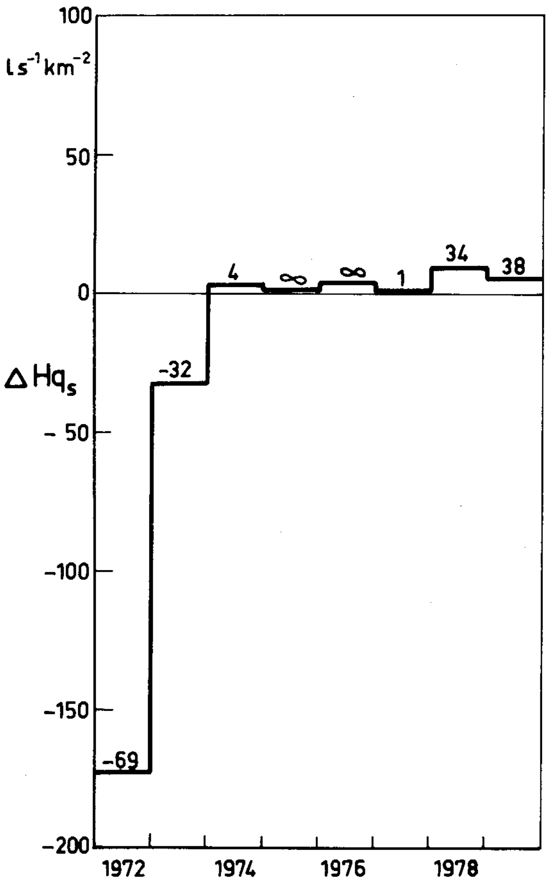

Fig. 33. The change in summer maximum runoff caused by sub-drainage of the Hovi basin. The figures at the top of the columns indicate the percentage of the change.

< 5 per cent risk.

Winter minimum runoff (30 days minimum during 1 January to spring flood) was increased in all years after sub-drainage. The average increase of 30 days winter minimum runoff was 0.11 $l\ s^{-1}\ km^{-2}$ or 157 per cent as compared with 'undrained' runoff. The increase was statistically significant at the < 1 per cent risk. Before sub-drainage there was no runoff in some winters. After the treatment, runoff has not ceased in any winter although it has still been small. During the post-treatment period there was a decreasing trend in runoff. The purified trend was statistically significant at the < 5 per cent risk.

Summer minimum runoff (30 days minimum during 1 June to 31 October) increased in all years but one. The average increase was 0.04 $l\ s^{-1}\ km^{-2}$ or 200 per cent of the calculated value. This increase was significant at the < 0.1 per cent risk. No trend during the post-treatment period was noticed.

In general, the flow peaks were considerably lower in the post-treatment period than in the calibration period. This was also the case on the control basin.

6.4 Discussion

Sub-drainage resulted in a drastic change in the surface runoff. Any notable surface runoff occurred only during snowmelt, if soil frost was thick and solid. In summer maxima no surface runoff occurred, practically speaking. The changes in the distribution of runoff between surface and subsurface runoff could be expected to have an effect on water quality and on the wash-out of chemical compounds. The first results from this study support this assumption. The spring maximum runoff, measured from sub-drains, amounted to 170 to 200 $l\ s^{-1}\ km^{-2}$, supporting the design practice of sub-drainage in Finland. Runoff from sub-drains (R_s in $l\ s^{-1}\ km^{-2}$) could be expressed as a function of frost depth (F_d in cm) as follows: $R_s = -2.0\ F_d + 170$, $R = -0.857$.

With regard to the changes of total runoff, no dramatic changes were observed. Some reduction in maximum runoffs and growth in minimum runoffs occurred, but they were not significant in general. A tendency towards the pre-drainage state was evident in later stages, although it was not yet significant.

A remarkable increase in the sub-drained area of Finland has been planned by the end of this century. It emphasizes the importance of studying this subject in various conditions.

7. INFILTRATION AND ITS DEPENDENCE ON SOME PHYSIOGRAPHIC FACTORS IN THE KYLMÄNOJA BASIN

7.1 Methods and measurements

From 1973 on, infiltration measurements were carried out in the Kylmänoja basin at Vihti, in southern Finland (Seuna 1983 b). A modified double ring infiltrometer was used with the diameter of

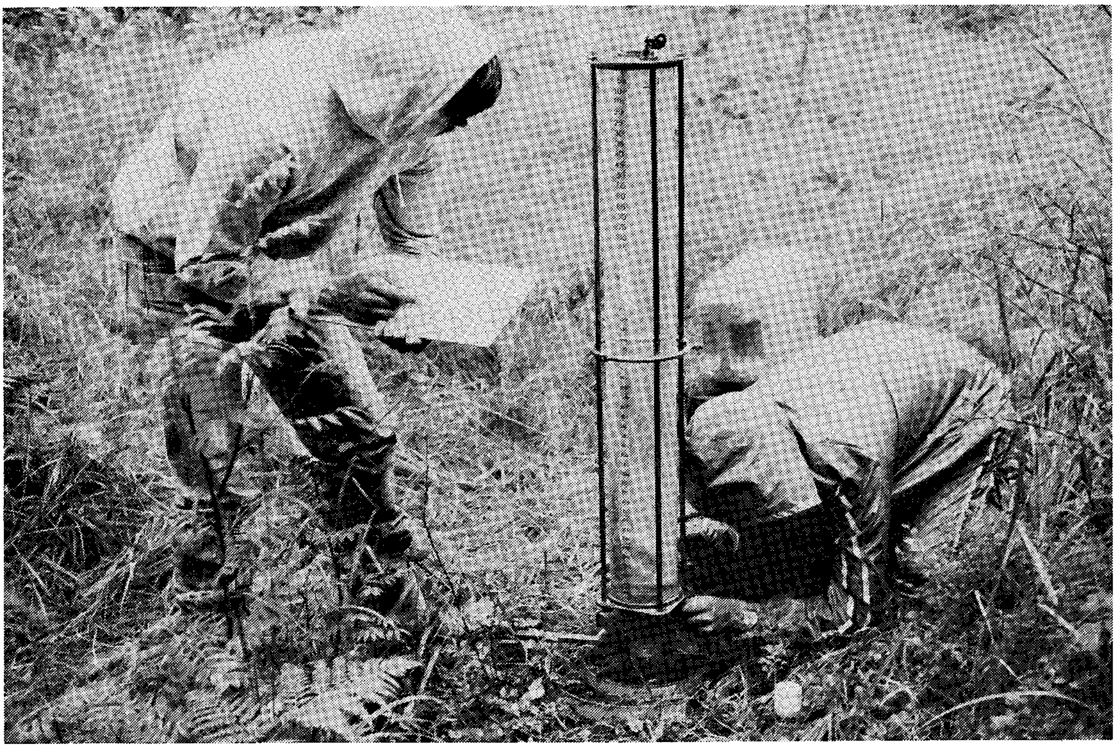

Fig. 34. A double-ring infiltrometer with a burette used for the infiltration measurements at Vihti, in southern Finland in 1973 to 1981.

the inner ring equal to 22.8 cm and that of the outer ring equal to 35.6 cm and with the height of the both rings being equal to 15 cm. A burette with valves was installed above the inner ring in order to maintain a constant water table in the inner ring (Fig. 34). The intention was to adjust the water table by means of the Mariotte's vessel, but sufficient accuracy could not be achieved mainly due to the surface tension of water. For this reason a manual adjustment and sharp nibs were used in the both rings to maintain the desired water table.

The infiltration rate (f, mm min^{-1}) vs. time (t, min) curves were fitted to each measurement using the formulae of Philip (1954), Horton (1940) and a logarithmic equation.

Philip equation $f = S_1 t^{-1/2} + A_1$, where (48)

S_1 = measure indicating sorptivity
A_1 = constant

Horton equation $f = f_c + (f_o - f_c)e^{-kt}$, (49)

where
f_o = initial infiltration
f_c = infiltration capacity
k = constant

Logarithmic function

$$f = \frac{K}{\lg (t + 1)} + B \lg (t + 1) + A, \qquad (50)$$

where K, B, A coefficients to be determined.

The fitting of the equations (48) and (50) was carried out using a normal regression analysis, the equation (49) using iteration.

In order to visualize the phenomenon of infiltration, a separate experiment using tracers, Rhodamin B liquid and Methyl violet, was made. After two hours of infiltration it could be noticed from the excavation that the penetration of water was concentrated almost entirely in big pores, fissures or holes. No even distribution of the colour existed, obviously, because the capillary movement of water to the micropores is much slower than the percolation of water to even relatively deep layers.

7.2 Fitting of the infiltration equations

The equations mentioned before, were fitted to 214 infiltration measurements. In general all these equations could be fitted rather well to the measured data (Table 10).

Of these equations the fit of the Philip formula was clearly weaker than the two others. The Philip formula easily tended to give much too low values for the infiltration capacity and respectively somewhat high values after the first 20 minutes. The infiltration capacity f_c determined using the Horton formula was rather often too high; in almost half of the cases more than 20 per cent too high, although the fit was good otherwise.

7.3 Dependence of infiltration on some physiographic and meteorologic factors

7.31 Soil characteristics

The dependence of infiltration on soil characteristics, especially, was studied using the measurements from seven fixed points, from where soil samples were taken after 4—5 infiltration measurements. The averages of some soil characteristics are given in Table 11.

Table 10. Distribution of the correlation coefficients of the 214 fittings using the infiltration formulae of Philip (1954), Horton (1940) and a logarithmic modification (equation 50).

Range of correlation coefficient	Percentage of the fittings Philip	Horton	Log
>0.99	3	25	13
0.950—0.99	19	38	55
0.900—0.949	22	19	19
0.850—0.899	16	6	4
0.800—0.849	14	4	2
0.700—0.799	13	4	3
<0.700	13	4	4
Total	100	100	100

Table 11. Soil characteristics of the measuring points K1—K7 at Vihti.

Point	Soil characteristic: Percentage clay %	Grain size (mm) of the proportions of 10 %	50 %	90 %	d_{60}/d_{10}	Organic layer cm
K1	10.3	0.0038	0.137	1.08	79.3	0
K2	0	0.11	1.17	3.32	5.2	4.8
K3	0	0.08	0.28	1.03	4.1	2.0
K4	10.6	0.0022	0.022	0.41	23.4	1.5
K5	25.0	0.001	0.0075	0.28	16.5	0
K6	32.0	0.001	0.0051	0.05	10.0	0
K7	0	0.060	0.22	1.40	5.3	3.5

Soil was defined as graded soil, if the ratio of d_{60} (= grain size 60 per cent finer by weight) and d_{10} (= grain size 10 per cent finer by weight) was less than five.

7.32 Antecedent precipitation index

As a measure of moisture conditions the antecedent precipitation index (51) was used

$$API_n = k \cdot API_{n-1} + P_{n-1}, \tag{51}$$

where API_n = antecedent precipitation index of the n th day in mm
API_{n-1} = the index of preceding day (n—1) in mm
P_{n-1} = precipitation of (n—1) th day in mm
k = coefficient of the month

The coefficients k were determined so that the API of each month corresponded to the average soil water content of the same month in the 25 cm topsoil of a cultivated land (Seuna 1977 b and 1983 b). For the initial value 100 mm in the beginning of May was chosen, which corresponds to the field capacity of this soil. The following k-values for various months were then obtained:

May	0.980
June	0.968
July	0.955
August	0.960
September	0.972
October	0.983
November	0.990

7.33 Influence of soil characteristics and moisture conditions on infiltration capacity

In order to study relationships between the infiltration capacity and soil characteristics the infiltration measurements were classified according to the measuring point (K1—K7) and API (80—100 mm, 51—79 mm and 30—50 mm).

The infiltration capacity obtained from the individual measurements could differ considerably on the same plot, even in similar moisture conditions, due to some big fissures of the soil.

For this reason group means (n = 21) were used in the regression analysis instead of the individual measurements.

The best independent variables in the regression analysis were the thickness of organic layer (r = 0.66), the grain size of the finest 10 per cent of soil (r = 0.64), the percentage of clay (r = —0.63) and the percentage of soil coarser than 0.2 mm (r = 0.62). The combination of API and the gradedness of soil correlated well with infiltration capacity ($API/(d_{60}/d_{10})$, r = 0.74; $(API)^2/(d_{60}/d_{10})$, r = 0.78).

The equation (52) explained 71 % of the total variance of infiltration capacity f_c (mm min^{-1})

$$f_c = 0.38\ O_t + 0.0021 \frac{API^2}{d_{60}/d_{10}} + 1.30$$

$$R = 0.845 \qquad (52)$$

The effect of antecedent precipitation index varied in separate measuring points. In the points K2, K3, K6 and K7 the infiltration capacity was in dry soil usually smaller than in somewhat moister soil. In individual cases very low infiltration values were observed in exceptionally dry soil. After the first rainfall infiltration generally increased remarkably, probably because of the softening of the soil surface. This procedure was followed in the points, where the soil was highly graded. They were also rich in fine fractions. In moraine areas, infiltration capacity of dry soil exceeded that of moist soil.

The relationship between the infiltration capacity and soil characteristics was also studied using each of the seven measuring point as one group. The API-means of the groups were almost identical and the group means could thus well be compared. The infiltration capacity correlated significantly statistically (risk < 1 per cent) with the thickness of organic layer O_t(r = 0.95), grain size of 10 per cent fraction d_{10} (r = 0.91), the percentage of clay G_c (r = —0.89) and the percentage of material coarser than 0.2 mm (r = 0.88). The equation (53)

$$f_c = 0.69\ O_t + 1.90,\ R = 0.946 \qquad (53)$$

explains 90 per cent and the model (54)

$$f_c = 0.47\ O_t - 0.041\ G_c + 2.7$$
$$R = 0.976 \qquad (54)$$

95 per cent of the variance of f_c. Average curves of infiltration for the points K1 and K3 are presented in Fig. 35.

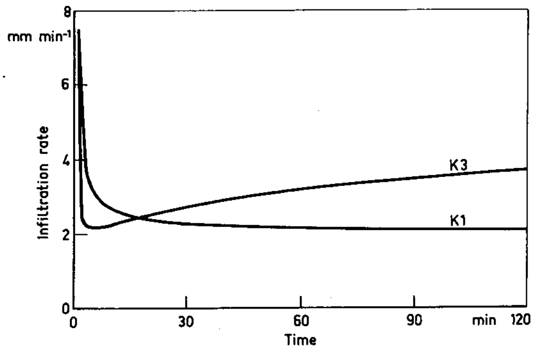

Fig. 35. Typical curves of infiltration rate at the sites K1 and K3 at Vihti. At the site K3 a stony till is situated at the depth of half a meter.

7.4 Discussion

Infiltration measured using a double ring infiltrometer could be presented satisfactorily with different infiltration equations, such as the two parameter Philip, but especially with the three parameter Horton and a logarithmic equation. The measured infiltration capacity averaged 2.7 mm min^{-1}, which is obviously much greater than in the basin scale in nature. This difference was also pointed out earlier (e.g. Hills 1970, Scoging and Thornes 1979). Reasons for high infiltration rates could be lateral flows, hydrostatic pressure or disturbance of soil in connection with the measurement. The biggest difference between a basin and a ring infiltrometer has probably risen, however, from the fact that in a basin water has access from the rainfall area to drainage network, but in the infiltrometer no access from the ring exists except for the one downwards. Lateral flows can be considered negligible judging from the experiment with dye dilution.

In the point K3 the infiltration curve appeared to be rising except for the first ten minutes. The exceptional form of the curve evidently stemmed from the bottom soil, which at a depth of 50 cm was a stony till.

Soil characteristics, especially the finest fractions and the organic matter, explained infiltration capacity f_c well. On the other hand moisture conditions appeared to affect in two ways. In moraines infiltration capacity of dry soil was higher than for moist soil, as could be expected. On the contrary, in graded soil with plenty of fine fractions the infiltration capacity of moist but not thoroughly wet soil was higher than that of a very dry soil.

All the observational data logically followed this procedure, but more measurements in different soils would be needed to bear this out.

The phase of summer seemed to affect in such a way that infiltration was higher in spring than in late summer in respective conditions. This has been stated also by Schumm and Lusby (1963). On the other hand, infiltration capacity was not irrespective in preceding moisture conditions as reported by Papadakis and Preul (1973).

Considering the practical use of infiltration measurements with a ring infiltrometer the transfer of the results to the basin scale needs much more research and could even turn out to be impossible in the variable soil complex of Finland. On the other hand the average infiltration index evidently can be estimated from some soil characteristics and also relative differences of various soils or conditions could be determined using the infiltrometer. All these estimations, however, require several replicates of measurements in order to eliminate the influence of scatter caused by the large pores and fissures inherent in the soil.

8. CONCLUDING REMARKS

One of the primary objectives of small basin studies is to produce information for water resources planning and for the design of hydraulic engineering works. The hydrological influence of physiographic characteristics is essentially involved in design, but has also other importance, e.g. in evaluating hydrological consequences of human impact. Apart from an ordinary use as reference basins, small hydrological basins have been used in this set of studies as a tool for different purposes as follows.

8.1 Summary of findings

Direct transposition of data. As the first step, related to a direct transposition of the observational results, statistical characteristics of runoff quantities were analysed from the individual basins. Frequency analyses of these quantities were carried out for 37 basins, which had data series of not less than 10 years. Mean annual, spring, spring and summer maximum, together with 30-day winter and summer minimum runoffs were analysed. In the analyses straight or broken lines were fitted by eye. In order to avoid the effect of outliers in the relatively short series computational fitting was not used. The use of a broken line was based on the assumption that samples consisted of data from two separate populations, as is certainly the case for minimum runoffs. The Gaussian distribution was chosen for the annual and spring runoff, the Gumbel distribution for the maximum runoffs and the Weibull distribution for the minimum runoffs on the basis of try-out and previous experience.

From the frequency analyses runoff quantities with return periods of 10 and 20 years were determined. The return period of 20 years has been widely used as a basis of designing hydraulic engineering works in Finland.

These frequency analyses might be applied for ungaged basins by direct transposition. This would, however, require a great number of basins, and still the comparison could give a highly erroneous result.

Regression analysis. To improve the applicability of the statistical characteristics, regression equations were computed using physiographic characteristics as independent variables. The whole network was used as a data set to provide ranges of physiographic characteristics wide enough to permit a derivation of these relationships.

Characteristics, readily available from maps and statistics, were chosen in order to facilitate the application of these equations for ungaged basins.

In the regression analyses mean and exceptional (with return period of 20 years) maximum runoffs could in general be explained satisfactorily using two to four physiographic variables. The ratios of the instantaneous and daily maxima could be explained much better than those of the exceptional and average floods.

The most important groups of variables were soil factors, especially the percentage of fine soils or impermeable surfaces, the location of the basin including altitude, and for spring maxima the tree stand. Altitude had much the nature of an overall index; high altitude in Finnish conditions also means northern location, high water equivalent of snow ($r = 0.82$), low percentage of cultivated land ($r = —0.61$) and fine soils ($r = —0.55$), and low annual temperature ($r = —0.76$). Fine soils were especially decisive for summer maximum runoff, whereas open areas better explained spring maxima, in relative terms. Density of drainage network increased the peaked tendency of flood, as did the smallness of the basin for summer maxima. As far as the terrain types were concerned, cultivated land affected spring maxima; indicating fine soils, it also had an effect on summer maxima.

The topography of the basin did not explain maximum runoff as well as could be expected; this might be due to two contradictory factors associated with the Finnish topography, namely land slope and coarse soils. The geometric factors, such as basin form, did not prove to be significant. These could be more important for larger basins. Of climatological factors long-term averages of air temperature, precipitation and water equivalent of snow were all important factors influencing maximum runoff.

The objective of the regression analyses was for the most part a practical one, i.e. to produce models comprising readily available parameters and having a satisfactory degree of accuracy to be used in design of hydraulic engineering works. This was achieved rather acceptably, although some modifications, especially the multiple ones, should be tested in future work.

Regression equations have their serious limitations from the theoretical point of view, but some clues on the actual physical effects are obtained from these equations. The true quantitative effects of the physiographic characteristics are, however, easily obscured by intercorrelation of the characteristics or by other factors influencing simultaneously. The effects given by stable regression coefficients could be considered to indicate real effects, however. In this study number of relationships showed a remarkable stability in different combinations of regression equations. Such were growing stock, altitude and the percentage of cultivated land for spring maximum runoff, and the percentage of fine soils for summer maximum runoff.

Control basin method. For investigating the quantitative effects of some characteristics, paired basins and a control basin study were employed. Hydrological consequences of forestry drainage were studied in a long term study of Huhtisuo, in south-eastern Finland and in a short term research of Ylijoki, in northern Finland. The influence of sub-drainage was studied at the Hovi basin, in southern Finland.

In the Huhtisuo study, forestry drainage remarkably increased all runoff quantities. An average increase of 30 per cent in mean annual and spring maximum runoff were observed during the first ten years, while the increase in summer maximum and minimum runoff was even greater, in relative terms. The pre-drainage stage was almost attained after 15—20 years from drainage.

In the Ylijoki study, spring maximum did not increase, while the other runoff quantities seemed to increase after drainage. On the other hand, sediment discharge increased many times over, during the first two years after drainage. The annual load of suspended solids amounted to about ten tons per square kilometer for the whole drainage basin and from a small ditching area to about 230 t km^{-2} during the first spring flood after the drainage.

Sub-drainage of cultivated land did not result in any dramatic changes in the hydrology of a basin, except for the cease of surface runoff after sub-drainage. Some increases in annual and minimum runoffs and a decrease in summer maximum runoff were observed. During the first five to seven years after sub-drainage any notable surface runoff was observed only during spring maxima, when soil frost was exceptionally thick and solid. Spring maximum runoff from subdrains (R_s, l s^{-1} km^{-2}) could be expressed as a function of soil frost thickness (F_d, cm) as follows: $R_s = -2.0\ F_d + 170$.

The experience obtained, ascertain that quantitative information from control basin studies are supplied on the hydrological consequences after a treatment of a basin. The results are rather indisputable, if the requirements of the control basin method are fulfilled.

The method is, however, time and money consuming. For this reason multidisciplinary utilization of this framework should be tried and several consequences should be studied simultaneously. In the light of this experience it would be extremely important to adopt a policy of commencing control basin studies before a certain treatment or change has been carried out on a large scale, or even better, before treatment has begun at all.

Process studies. Concerning process studies, an attempt was made to study infiltration. A modified double ring infiltrometer was used for the measurements. Some infiltration equations, such as the equations of Philip and Horton and a logarithmic equation, were fitted to the measurements with a satisfactory level of accuracy.

The infiltration capacity given by these measurements was especially influenced by the finest fractions of soil. Low infiltration capacity was observed in graded fine soil, when it was dry. After the first light rainfall the infiltration increased, which was not the case with the ungraded soils. The quantitative application of ring infiltrometer measurements to soil complex of basin scale leaves a lot to be desired as far as interpretation is concerned, mainly because of the high rates given by the ring measurements. The measurements should also be combined with the other processes at the scale of a basin in future investigations.

From a practical point of view information on the permeability of soil measured in situ would be extremely useful both hydrologically and agriculturally, considering the impact of modern agriculture on soil.

8.2 General importance of the results

The significance of the basin studies, as described here, can be evaluated by comparing the scientific and economic importance of the results, the possibility of obtaining respective results using other methods and the costs of these studies.

The most important conclusions on a problem-oriented basis can be summarized as follows:

1. the fit of frequency lines by eye can be regarded as an acceptable method of avoiding the effect of outliers in a rather short series
2. a straight line or two intersecting lines are with good reason to be preferred to a curved fit in this case; separate populations support the use of a "dog-leg"
3. design values of maximum runoff can satisfactorily be estimated for ungaged basins, using two to four physiographic parameters, readily available beforehand from maps and statistics for Finnish conditions; a set of nomographs serve as a practical means in designing hydraulic engineering works
4. forestry drainage in most cases results in remarkable changes in the hydrology and sediment transport of a basin, during the first post-drainage years
5. the largest and the most unanimous of the hydrological changes in this respect are the increases in minimum flows, in summer maximum runoff and in annual runoff; for the change in spring maximum runoff the results from small basins are not completely parallel, which is also supported by other studies in Finland
6. increases in sediment discharge may be drastic due to forestry drainage, if erodible materials are available
7. the effects of forestry drainage decrease with time; for hydrological changes the pre-drainage level is reached in 15 to 20 years, roughly speaking; for sediment discharge high yields in later years may be expected only from exceptional floods, in Finnish conditions, if erobidle soils are available
8. sub-drainage influences a drastic decrease in surface runoff; notable surface runoff occurs after sub-drainage only during snowmelt if soil frost is thick and solid; changes in the proportions of surface and sub-surface runoff could be expected to reflect in the water quality and in the washout of chemical compounds and some clues for this have been obtained
9. spring maximum runoff, measured from sub-drains, amounts to 170—200 l s^{-1} km^{-2} supporting the present design procedure of sub-drainage in Finland
10. rate of infiltration, measured using double ring infiltrometer, can evidently be simulated well with infiltration equations, and the infiltration capacity can be explained rather satisfactorily using soil characteristics, such as the percentage of fine soils and the thickness of the organic layer
11. the application of ring infiltrometer values to the basin scale requires a lot from calibration, due to the different order of their magnitude compared with a natural basin and due to a large scatter of ring measurements; a successful measurement of infiltration would undoubtedly improve possibilities to synthetically develop physically-based models for drainage basins.

The economic importance of the problems described, is indisputable in Finnish conditions. Statistical characteristics of runoff quantities and methods to estimate them, are necessary for designing hydraulic engineering works and for water resources management. Small basins are not the only tool to produce this information, but it is often these particular types of basins, which are the ungaged ones. For this reason the need of statistical runoff values and of practical design models using readily available physiographic characteristics, is emphasized for small basins.

On the other hand, quantitative information on the consequences due to land use changes or other human impact can not usually be obtained from large basins, e.g. due to undesired simultaneous changes. In this set of studies, effects of two of the most comprehensive land use changes in Finland were studied quantitatively. Forestry drainage is by far the most comprehensive land use change carried out in Finland, comprising about one fifth of Finland's land area by 1980. Sub-drainage amounts today to some 800 000 ha or 32 per cent of the cultivated land of Finland and a changeover of one million hectares has been planned until the end of this century. In this light the significance of the studies employing small basins is considerable, although a final and general answer can not be obtained from one or two cases supported by regression analyses.

For process studies, the utilization of the Finnish small basins has been very limited, so far. The example of infiltration, discussed here, was more for giving clues for future studies than for finding readily applicable conclusions.

With regard to the costs of basin studies, a figure of about 70 000 FIM to establish a basin and 10 000 FIM a year for the operation, could be presented. The benefits obtained from the basins can be well considered to meet these costs. Efforts for multidisciplinary studies should still, however, be strengthened, in order to maximize the benefits of basin studies.

8.3 Aspects for future development of basin studies

The importance of the physiographic characteristics and their influence on hydrological quantities of a basin is for the most part the practical one. In water resources planning including hydraulic engineering works, especially, the influencing factors known in advance are of primary importance, but also in the operational use of water resources these factors improve the fit potential of prediction. Preliminary results of the applications of remote sensing allow a conclusion that, using this method, distributions of physiographic factors of large basins can in the near future be determined much more easily and precisely than until now. Employing satellite imagery, physiographic characteristics such as cultivated lands, water surfaces, open bogs and growing stock can be estimated with a sufficient accuracy (Kilpelä et al. 1978). For example the volume of growing stock, which was one of the most decisive factors for spring maximum runoff, can be obtained for basins larger than 10 square kilometres with about 10 per cent accuracy (Saukkola 1982, Kilpelä et al. 1978). By combining the digital information from the satellite imagery with the coordinates of water divide, the areal values of these physiographic characteristics can be obtained. A joint project between the National Board of Survey and the Technical Research Centre of Finland will be started for the realization of this. An advantage of frequent updating of the information is provided by this method.

The digital form of map characteristics offers a practical solution for the use of this information on large basins. Plans for such a digitalization exist in the National Board of Survey. Furthermore a joint project between the Geological Survey of Finland and the National Board of Survey aims to combine information on soil characteristics with basic maps made on a scale of 1:20 000.

At present forest cover is studied with high accuracy for large areas in connection with national inventories carried out by the forest administration. These inventories may not, however, produce information frequent enough in space and time to allow the utilization in river basins, except for the largest ones. In general, the new methods described above provide good premises for utilization of physiographic characteristics also at the scale of river basins.

Small basins serve as a natural framework for several purposes in hydrological research. Because of rather high expenses, interdisciplinary research strategy should be practised. This has also been pointed out in Unesco's international hydrological programs and in the international hydrological meetings, e.g. in Helsinki in 1980 and in Bern in 1982. Possibilities to use small basins as a basis for environmental protection control have been discussed by the Working Committee for Environmental Data of the Nordic Council for Ministers (1981). The aspects of instrumentation, drainage area and number of basins are critical factors, as far as the costs and the benefits are concerned. It is clear that the larger the drainage area, the more observations are needed, if the same accuracy is required. For example, in order to obtain 75 per cent of areal errors in daily precipitation smaller than 20 per cent, 4, 5 and 6 rain gauges are needed for a 10, 50 and 100 km^2 basin, respectively (Toebes and Ouryvaev 1970).

On the other hand, the level of instrumentation has a great influence, as far as the costs are concerned. A high level of instrumentation is, however, a necessary requirement, for an apt process study. If this is applied to the scale of a basin, the requirement of a sophisticated instrumentation applies, not only to one hydrological element, but to all the components of the water balance and all the phenomena associated with these components. This procedure leads to an idea of a field laboratory, furnished by a small basin. Opinions in favour of such field laboratories were presented in the aforementioned Helsinki meeting in 1980 and similar ideas for master sites have also been presented earlier (e.g. Toebes and Ouryvaev 1970).

Apart from field laboratories a number of basins are necessary to provide a sufficient range of physiographic and meteorologic factors, when hydrological values for the design of hydraulic engineering works are needed. This information cannot be substituted by other means, although opinions in favour of generated data sets have been presented still in the 1970's.

Furthermore, the length of the observation series should be long enough to permit a reliable derivation of statistical characteristics of hydrological quantities. In this respect, periods shorter than ten years have not much value, except when supported by a long series of an adjacent basin.

For some purposes, a somewhat shorter period could produce results. This could apply to process studies especially, and also to experimental studies, in some cases. The experimental studies, however, utilizing an ordinary control basin technique, generally require, a study period of about ten years or more to obtain results having a statistical significance.

Considering the hydrological effects caused by basin changes, the identification of these effects is often not possible from large basins. This is due to e.g. simultaneous impacts of several changes, or the difficulty in controlling and identificating the changes. The new methods of remote sensing will probably decrease the difficulties in this respect.

In Finland a special problem, considering the applicability of the results of small basins, is caused by lakes. It has been discussed, whether or not the small research basins should include lakes. As far as the general picture of the Finnish terrain is concerned, small basins should also contain lakes. The lakes would, however, so decisively affect runoff pattern of such a small basin that the factors affecting runoff from land area would be completely obscured. Therefore most of the utilization, described e.g. in this paper, would have failed, if these basins had contained lakes. In addition to this, the role of a lake in a basin is somewhat different from that of other physiographic factors. In a way it is more mechanical and subject to direct computation. These reasons justify the conclusion that more benefits with practical importance are obtained from basins without lakes than from those with lakes.

Due to the geological conditions in Finland — an igneous bedrock below fairly shallow soil layers — the water divides of even small basins can reliably be determined.

The experiences obtained during half a century from small basins in Finland, justify to conclude that a national network of small basins comprising both experimental and natural basins, is a useful tool. As a basis for obtaining values and relationships for various design problems, such a network can be considered necessary. From the observational point of view the drainage area should not exceed 100 to 200 square kilometres. The number of basins required, depends on the range of physiographic characteristics provided by the basins. If a representative variation of these factors is achieved, a network of some thirty basins could be sufficient. More basins are needed, if the range of essential characteristics, included in the basins, is poor. For Finnish conditions this means about one basin for 10 000 km^2, which could be considered sufficient for a reach of ten latitudes, for an altitude variation of some half a kilometre and for relatively uniform climatic conditions. For more mountainous regions with greater climatic variation this figure may not be sufficient.

Some of the basins should serve as experimental ones, to enable an interdisciplinary study of the impacts of the most important activities that have been performed, or even more important that are going to be carried out, in that particular region.

From a scientific point of view a few of the basins should be well-equipped field laboratories to enable to study processes at the scale of a basin. These basins should, however, be a part of the whole set of basins, to be also employed for developing relationships or for control basin studies.

ACKNOWLEDGEMENTS

Data used in this study have been provided by the National Board of Agriculture until 1970 and from then on by the National Board of Waters. The local observers — about 200 in number — have been key persons in producing the observational data. The construction and maintenance of the measuring weirs have been carried out by the Water Districts' offices. Mr. Veikko Salmipuro has been taken part in the maintenance of network and also carried out some specific measurements.

Of the numerous persons, who participated in the processing of the data, I especially wish to thank Messrs. Juhani Eloranta and Teppo Järvi, who mainly attended the computational tasks, Väinö Malin for assisting in statistical interpretations, Timo Nieminen for assisting in data collection, and Bertel Vehviläinen for making certain statistical computations.

Prof. Seppo E. Mustonen has given valuable comments and proposals during the whole work, for which I am most grateful. I also want to thank Prof. Matti Wäre, Prof. Matti Viitasaari and Mr. Esko Kuusisto for commenting the manuscript, and Mr. Risto Kuittinen for giving information on remote sensing and related subjects.

Assistance in bibliographic questions was given by Ms. Pirjo Lipponen, the typing of the manuscripts was carried out by Ms. Eeva-Liisa Alanne and Ms. Pirkko Seppänen, the numerous illustrations included in the work were drawn by Ms. Terttu Halme and Ms. Irma Nylander, and the layout was made by Ms. Raili Malinen.

The English language was revised by Mr. Peter Dodds, Ms. Auli Niemi and in part by Ms. Tarja Pyykkö.

I wish to express my gratitude to all the persons, who contributed to this work.

Finally I want to thank the Sven Hallin's Research Fund for giving financial support for publication.

Tuusula, January 1983

Pertti Seuna

LOPPUTIIVISTELMÄ

Tässä tutkimuksessa on käsitelty kuutta erillistä tutkimusta, joissa on käytetty pieniltä valuma-alueilta saatua aineistoa. Tarkoituksena on ollut tarkastella pienten alueiden käyttökelpoisuutta sekä tieteellisen hydrologisen tutkimuksen että käytännön vesirakennustoiminnan kannalta.

Hydrologiset valuma-alueet ovat olleet eräs hydrologisen tutkimuksen peruselementtejä yli 300 vuoden ajan eli siitä saakka kun tieteellistä hydrologista tutkimusta katsotaan harjoitetun. Valuma-alueen koolla on oleellinen vaikutus alueen käyttöön tutkimusvälineenä.

Pienten alueiden tutkimuksella on Suomessa puolen vuosisadan perinteet. Pienillä alueilla tarkoitetaan tällöin yleensä jokea pienempiä (< 200 km^2) vesistöalueita. Pienet alueet muodostavat luonnollisen tutkimuskehyksen, jonka ominaisuudet ovat homogeenisempia sekä helpommin selvitettävissä ja hallittavissa kuin isojen alueiden. Myös tarkkojen havaintotulosten saaminen on yleensä mahdollista pienemmin kustannuksin kuin suurilta valuma-alueilta.

Pienten alueiden havaintotulokset eivät yleensä ole käyttökelpoisimmillaan sellaisenaan, vaan ne vaativat sopivaa käsittelyä ja tulkintaa. Niinpä esimerkiksi hydrologista simulointia tarvitaan pienille alueille vain harvoin, päinvastoin kuin suurille alueille. Simulointi pienellekin alueelle saattaa kuitenkin tulla kysymykseen tutkittaessa hydrologisia muutoksia vain yhden alueen havaintojen perusteella. Tavallisesti muutoksien tutkimisessa käytetään kuitenkin alueparia ja ns. vertailualuemenetelmää.

Pienten alueiden tutkimusten tarkoituksena on ollut ensisijaisesti hydrologisen tiedon tuottaminen vesirakenteiden ja vesien käytön suunnittelun tarpeisiin. Tällöin ovat tärkeitä sekä hydrologisten suureiden tilastolliset tunnusluvut että niihin vaikuttavat tekijät. Maankäytön muutokset ovat Suomessa kansainvälisesti arvioiden yleensä pieniä. Poikkeuksen tästä muodostaa kuitenkin metsäojitus, joka 1970-luvun loppuun mennessä on ulottunut lähes viidennekselle Suomen maa-alasta. Myös eräitä muita metsänhoitotoimia, kuten kivennäismaiden aurauksia, metsänhakkuita ja -viljelyä suoritetaan merkittävässä laajuudessa. Peltojen salaojitus on SARA-ohjelman toteutuessa muodostumassa varsin huomattavaksi maankäyttömuutokseksi; suunnitelman mukaan peltojen salaojitus lisääntyy 1970-luvun lopun 32 prosentista 70 prosenttiin tämän vuosisadan loppuun mennessä. Näiden muutoksien seurausvaikutuksia on selvitelty pienten alueiden tutkimuksissa jo aiemmin (Mustonen ja Seuna 1971a, Seuna 1980, 1982a, b, Seuna ja Kauppi 1980, 1982).

Tässä tutkimussarjassa pieniä valuma-alueita on käytetty tutkimusvälineenä neljällä eri tasolla, yksittäisen valuma-alueen havaintojen käyttönä sellaisenaan, koko havaintoverkkoa yhdessä tuottamaan regressiomalleja, alueparin ja vertailualuemenetelmän avulla sekä prosessitutkimukseen.

Yksittäisen valuma-alueen käyttö. Valuma-alueille, joilla on käytettävissä vähintään 10 vuoden havaintosarja, laadittiin valumasuureiden toistuvuusanalyysi (Seuna 1982c). Käytetyt 37 valuma-aluetta käyvät ilmi kuvasta 1 ja taulukosta 1. Analysoidut valumasuureet olivat vuoden keskivaluma, kevätvalunta (1.3.—31.5.), kevät- ja kesäylivaluma sekä vuorokausiarvona että hetkellisenä huippuna, 30 vuorokauden talvi- ja kesäalivaluma. Vuoden keskivalumalle ja kevätvalunnalle käytettiin normaalijakaumaa, ylivalumille Gumbelin äärimmäisten arvojen jakaumaa ja alivalumille ns. Weibullin jakaumaa eli Gumbelin jakaumaa, jossa valuma-akseli on logaritminen. Pistejoukkoja kuvaamaan sovitettiin silmävaraisesti suora tai kaksi toisensa leikkaavaa suoraa. Havaintosarjan lyhyyden ja havaintosarjoihin sisältyneiden poikkeavien arvojen vuoksi analyyttistä menettelyä ei voitu käyttää. Jakaumat valittiin siten, että pistejoukot mahdollisimman hyvin asettuivat suoralle, toistuvuuspaperien käytön perusajatuksen mukaisesti. Käyräviivaisia kuvaajia ei myöskään havaintosarjojen lyhyyden vuoksi ollut syytä käyttää. Taitesuoran käyttö on perusteltua, mikäli havaintoaineiston voidaan katsoa muodostuvan kahdesta perusjoukosta kuten ainakin alivalumien osalta on asianlaita useina vuosina. Toistuvuusanalyysissa määritettiin keskimäärin kerran 10 ja kerran 20 vuodessa sattuvat valumat. Toistumisaika 20 vuotta valittiin, koska sitä yleisesti käytetään mitoituslähtökohtana vesirakenteiden suunnittelussa.

Yksittäisiä toistuvuusanalyyseja voidaan käyttää

tavanomaisen referenssialueen periaatteella siirtämällä tulokset suoraan tutkittavalle alueelle. Menettely on kuitenkin sangen epävarma, ellei alueita ole niin runsaasti, että niistä aina voidaan valita ominaisuuksiltaan tutkittavaa aluetta vastaava alue.

Regressiomallit. Toistuvuusanalyysin tulosten yleistämiseksi laskettiin kevät- ja kesäylivalumille joukko regressiomalleja (Seuna 1983a). Selitettävinä muuttujina olivat keskimääräinen ja keskimäärin kerran 20 vuodessa sattuva ylivaluman vuorokausiarvo ja hetkellinen arvo sekä keväälle että kesälle. Lisäksi laskettiin hetkellisen ja vuorokautisen ylivaluman sekä kerran 20 vuodessa sattuvan ja keskimääräisen ylivaluman suhteille regressioyhtälöitä. Selittävinä muuttujina käytettiin kartoilta tai tilastoista etukäteen saatavia aluetekijöitä sekä ilmastotekijöistä pitkän jakson keskiarvoja.

Valitut ylivalumien tunnusluvut oli yleensä mahdollista selittää käytännön tarpeisiin riittävällä tarkkuudella käyttämällä 2—4 muuttujaa. Hetkellisten huippujen ja vuorokausiarvojen suhde selittyi selvästi paremmin kuin kerran 20 vuodessa sattuvien ylivalumien suhde keskimääräisiin.

Parhaita selittäjäryhmiä olivat maaperätekijät, alueen sijainti ja korkeusasema sekä puusto. Hienot maalajit selittivät erityisesti kesäylivalumia kun taas avoimet alueet, lähinnä peltojen osuus, selittivät paremmin kevätylivalumia. Valuma-alueen korkeusasema, yleensä ilmaistuna alimman pisteen korkeutena, osoittautui erittäin hyväksi kevätylivaluman selittäjäksi, mutta se selitti hyvin myös kesäylivalumia. Korkeusasemaa on pidettävä eräänlaisena yleisindeksinä; sen suuri arvo merkitsee samalla pohjoista sijaintia, runsasta lumen määrää ($r = 0.82$), vähäistä pellon ($r = —0.61$) ja hienojen maalajien osuutta ($r = —0.55$) sekä matalaa vuoden keskilämpötilaa ($r = —0.76$). Valuma-alueen ala selitti voimakkaasti kesäylivalumia ja ylivalumien huipukkuutta, samoin teki uomatiheys, vaikka se jäikin yleensä alan rinnalla pois malleista. Alueen topografialla ei ollut — eikä geometrisillä tekijöilläkään — merkittävää vaikutusta selitettäviin muuttujiin, joskin kaltevuuden lisääntyminen lisäsi ylivaluman äärevyyttä, erityisesti kesähuippujen osalta. Ilmastotekijöistä pitkän jakson lämpötila, sadanta ja lumen vesiarvo olivat tärkeitä ylivaluman selittäjiä.

Regressiomalleja kehitettäessä kokeiltiin runsaat 1000 muuttujayhdistelmää, joista muutamat kehitettiin nomogrammeiksi (kuvat 7—14).

Regressioanalyysin käyttöön sisältyy joukko vakavia ongelmia, kuten selittävien muuttujien väliset korrelaatiot, muuttujien ja selitysvirheiden jakaumien epänormaalisuus sekä muuttujien vaihteluvälin kapeus tai vinous. Puhtaasti matemaattisin perustein olisikin regressioanalyysin käyttö monissa luonnontieteellisissä yhteyksissä hylättävä. Käytännössä tarvittavien muuttujayhdistelmien tuottamiseen regressioanalyysia on kuitenkin pidettävä käyttökelpoisena menetelmänä, vaikka todellisia fysikaalisia vuorosuhteita ei välttämättä aina saadakaan esille. Silloin kun muuttujan regressiokerroin eri muuttujayhdistelmissä pysyy vakaana, voidaan vuorosuhteen katsoa kuitenkin antavan informaatiota kyseisen tekijän todellisestakin vaikutuksesta.

Vertailualuetutkimukset. Valuma-alueiden maankäyttömuutosten seurausvaikutuksia tutkittiin vertailualuemenetelmää käyttäen. Metsäojituksen pitkäaikaisia vaikutuksia tarkasteltiin Ruokolahdella sijaitsevien Huhtisuon ja Latosuon valuma-alueiden avulla (alueet 44 ja 43, kuva 1), sekä lyhytaikaisia vaikutuksia Ylijoen ja Kotiojan valuma-alueiden perusteella (alueet 119 ja 120, kuva 1). Ylijoella mitattiin myös kiintoaineen kulkeutumista.

Huhtisuon ojitus — n. 40 % alasta — lisäsi kaikkia valuma-suureita huomattavasti erityisesti ensimmäisinä ojituksen jälkeisinä vuosina (Seuna 1982a). Ensimmäisen yhdeksän vuoden aikana kasvoivat vuosivalunta haihdunnan pienenemisen vuoksi sekä kevätylivaluma keskimäärin noin 30 %, kesäylivaluma yli kaksinkertaiseksi sekä alivalumat moninkertaisiksi "ojittamattomaan" verrattuna. Ylivalumien lisäys johtui pääasiassa ojituksen aiheuttamasta valunnan nopeutumisesta, alivalumien kasvuun vaikutti merkittävästi ohuehkon turvekerroksen alla oleva karkea mineraalimaa, johon kaivetut ojat ulottuivat. Ojituksen vaikutukset vähenivät ajan mittaan niin, että likimain alkuperäinen taso saavutettiin 15—20 vuoden kuluttua ojituksesta. Vuosivaluman ja alivalumien osalta laskevat trendit olivat tilastollisesti merkitseviä. Laskeva trendi oli todennäköinen myös ylivalumille, vaikka se ei ollutkaan tilastollisesti merkitsevä käytettäessä ilmastollisten vaikutusten suhteen korjattua aineistoa. Laskevien trendien voidaan katsoa johtuvan lähinnä männyntaimiston kasvun aiheuttamasta haihdunnan lisäyksestä ja lumen sulamisolojen tasaantumisesta sekä ojien vedenjohtokyvyn huononemisesta ajan mittaan.

Ylijoen metsäojitus Ranualla sekä pieni määrä metsänaurauksia eivät hydrologisessa mielessä aiheuttaneet erityisen suuria muutoksia (Seuna 1982b). Ojitukset suoritettiin pääosin vuonna 1979 ja ne käsittivät yhteensä 17 % valuma-alueesta. Ensimmäisten kahden ojitusta seuranneen vuoden perusteella lisääntyivät alivalumat merkittävimmin, noin 50 % vertailualueen perusteella laskettuna. Vuosivalunnan kasvu oli 10 % ja kesäylivaluman 35 % luokkaa. Kevätylivaluman pienenemiseksi voidaan arvioida noin 10 %. Kaikki nämä muutokset ovat lyhyen havaintokauden vuoksi varsin alustavia eivätkä ne ole tilastollisesti merkitseviä.

Sen sijaan kiintoaineen kulkeutuminen, laskettuna suspendoituneena sedimenttinä, kasvoi ojitusten jälkeen selvästi. Vuotuinen kiintoainekuorma 1980, ojitusten pääosaa seuranneena vuonna, oli 7.49 t km^{-2} ja vuonna 1981 12.65 t km^{-2}. Vertailualueen perusteella laskettu kasvu oli 1980 6.16 t km^{-2} eli 465 % ja 1981 10.48 t km^{-2} eli 483 %. Lyhyestä havaintokaudesta huolimatta nämä lisäykset olivat tilastollisesti merkitseviä (riski < 0.1 %).

Kiintoaineen kulkeutuminen lisääntyi erityisesti silloin kun valuma oli suuri. Kun lumen sulamiskautena jo ennen ojitustakin kulki 2/3 vuotuisesta kiintoainekuormasta, oli osuus ojituksen jälkeisenä aikana 91 %. Ojituksen jälkeen ilmeni myös kiintoaineen pitoisuuden ja valuman välille selvä riippuvuus ($S_s = aq^b$), jota ennen ojitusta ei sanottavasti ollut. Samalla tämä merkitsi sitä, että pienten valumien aikana kiintoaineen pitoisuus ei noussut, vaan pysyi suunnilleen ennallaan tai jopa hiukan laski.

Salaojituksen hydrologisia vaikutuksia tutkittiin Vihdissä Hovin alueella (Seuna ja Kauppi 1982). Vuonna 1971 suoritetun salaojituksen seurauksena pintavalunta lakkasi suureksi osaksi. Keskimäärin pintavalunta salaojituksen jälkeen oli 23 % vuosivalunnasta. Pintavaluntaa tapahtui merkittävästi vain keväällä sulamiskautena, mikäli routa oli rakenteeltaan vielä tiivistä ja sitä oli runsaasti. Kesäylivalumien aikana keskimäärin vain 2 % kokonaisylivalumasta oli pintavaluntaa. Kevätylivaluma salaojista (R_s, l s^{-1} km^{-2}) riippui roudan paksuudesta (F_d, cm) yhtälön $R_s = -2.0\ F_d + 170$ mukaisesti. Kevätylivaluman maksimiarvo 170—200 l s^{-1} km^{-2} salaojista tukee putkiston nykyistä mitoituskäytäntöä.

Vertailualueen perusteella laskettuna salaojitus lisäsi vuosivaluntaa 15 %, kevätvaluntaa 12 % ja alivalumat yli kaksinkertaisiksi. Valuntana on tällöin tarkasteltu pinta- ja salaojavalunnan summaa. Kevätylivaluma ei juuri muuttunut, mutta kesäylivaluma pieneni keskimäärin 36 % ja hetkellinen huippu vielä enemmän. Kesäylivalumilla oli nouseva eli lähtötasoa kohti palautuva trendi, joka ei kuitenkaan ollut tilastollisesti merkitsevä.

Prosessitutkimukset. Esimerkkinä prosessitutkimuksista tarkasteltiin Vihdin Kylmänojan valuma-alueella imeyntää ja sen riippuvuutta eräistä maaperätekijöistä sekä edeltävistä sadantaoloista (Seuna 1983b). Imeyntämittauksia tehtiin kahdeksana kesänä modifioidulla kaksoisrengasinfiltrometrilla. Imeyntämittauksiin, joita oli yhteensä 214 tapausta, sovitettiin Philipin, Hortonin ja logaritmista imeyntäyhtälöä. Kahden viimeksimainitun yhtälön sopivuus mittausaineistoon oli hyvä, kahdessa kolmasosassa tapauksista ylitti korrelaatiokerroin 0.95. Philipin yhtälön sopivuus oli selvästi huonompi, korrelaatiokertoimista vain 22 % ylitti 0.95.

Mitattua loppuimeyntää selittivät parhaiten maalajin hienoimmat fraktiot, orgaanisen aineen määrä sekä esisadantaindeksi ja maa-aineksen lajittuneisuus. Pieni loppuimeyntä todettiin lajittuneissa maalajeissa pitkän kuivan kauden jälkeen. Se oli selvästi pienempi kuin kyseisellä maalajilla kosteana. Lajittumattomilla maalajeilla oli loppuimeyntä sitä pienempi mitä kosteammat esisadantaolot olivat.

Rengasinfiltrometrilla mitattu imeyntä ylitti selvästi sen, mitä luonnossa valuma-alueen mitassa esiintyy. Lisäksi yksittäisten mittausten hajonta likimain samoissakin kosteusoloissa ja samoissa maaperäoloissa oli suuri maassa olevien suurten huokosten ja reikien voimakkaan vaikutuksen vuoksi. Nämä tekijät vaikeuttavat huomattavasti imeyntämittausten suoranaista soveltamista valuma-alueen mitassa, mitä maaperän suuri epähomogeenisuus vielä hankaloittaa. Toisaalta imeynnän mittaaminen valuma-alueeseen sovellettavassa muodossa lisäisi epäilemättä mahdollisuuksia kehittää synteettisesti fysikaalisia valuma-aluemalleja.

Pienten alueiden hyödyllisyyttä tutkimusvälineenä voidaan arvioida niiden kustannusten sekä saatujen tulosten tieteellisen ja taloudellisen hyödyn perusteella. Lisäksi on otettava huomioon, ovatko tulokset tuotettavissa muilla keinoilla.

Valumasuureiden tilastollisten tunnuslukujen tarve on ollut ilmeinen niin kauan kuin vesirakennustoimintaa on harjoitettu. Samaa tarvetta palvelevat helposti saataviin maasto- ja ilmastotekijöihin perustuvat mallit. Pienet valuma-alueet eivät ole ainoa keino, jolla tätä informaatiota voidaan tuottaa. Usein kuitenkin juuri pieniltä alueilta puuttuvat omat havainnot kokonaan, mikä korostaa suunnitteluarvojen ja -mallien tarvetta juuri tämäntyyppisiä alueita varten.

Toisaalta osa pieniltä valuma-alueilta saatavasta tiedosta on sellaista, ettei sitä kvantitatiivisesti ole useinkaan mahdollista tuottaa isoilta valuma-alueilta. Erilaisten maankäyttömuutosten vaikutukset peittyvät isoilla alueilla helposti samanaikaisesti vaikuttavien muiden tekijöiden vaikutuksesta. Myös itse maankäyttömuutoksen mittaaminen ja hallinta tuottaa vaikeuksia.

Suomessa on pienten alueiden vertailututkimuksia tehty tähän mennessä metsäojituksen ja pellon salaojituksen vaikutuksista. Suomen oloissa nämä maankäyttömuutokset edustavat samalla kahta laaja-alaisinta ihmisen toimenpidettä, joiden taloudellinen merkitys on kiistaton. Vaikka yhden tai kahden yksittäisen tutkimuksen perusteella, joita regressioanalyysit tukevat, ei voidakaan saada lopullisia ja yleispäteviä vastauksia, on pienillä alueilla tässä suhteessa tärkeä merkitys.

Saatujen kokemusten perusteella tulisi pienten alueiden olla kooltaan yleensä muutaman neliökilometrin suuruisia, pääasiassa 1—100 km^2 suuruisia. Yli 200 km^2 alueilla ei tavallisesti enää ole erityispiirteitä, toisaalta havaintojen ja maastotekijöiden tarkka määrittäminen samoinkuin korkeat kustannukset muodostuvat rajoittaviksi tekijöiksi. Suomen geologisten olojen — erityisesti melko ehjän ja lähellä pintaa sijaitsevan peruskallion — vuoksi alueiden rajaus on mahdollista tehdä luotettavasti pienilläkin alueilla. Tällöin alle 1 km^2 suuruisiakin alueita voidaan käyttää, varsinkin vertailu- yms. erityistutkimuksiin.

Alueiden instrumentoinnissa joudutaan yleensä sovittelemaan alueiden lukumäärän ja instrumentoinnin täydellisyyden välillä. Jotta alueilla olisi merkitystä verkkona, olisi niitä oltava riittävästi; Suomen kaltaisissa ilmasto- ja maastovaihteluissa vähintään 1 alue 10 000 km^2 kohden. Tällöin on instrumentoinnissa tyydyttävä yleensä verrattain yksinkertaisiin ja vaatimattomiin ratkaisuihin, mitä voidaan myös pitää riittävänä. Erityisalueilla, esimerkiksi vertailu- ja prosessitutkimuksissa, pitäisi kuitenkin instrumentoinnin olla mahdollisimman monipuolinen ja tarkka. Näiden erityisalueiden, kenttälaboratorioiden, kustannukset nousevatkin tuntuvasti suuremmiksi kuin tavallisten alueiden.

Suomessa on käyty keskustelua siitä, tulisiko pienillä hydrologisilla tutkimusalueilla olla järviä. Alueiden yleisen edustavuuden kannalta niitä tulisi olla, sillä järvisyys on varsin tunnusomainen piirre suomalaisessa luonnossa. Järvillä olisi kuitenkin pienillä alueilla niin voimakkaasti erityispiirteitä tasaava vaikutus, että esimerkiksi tässä esitettyjä tutkimustuloksia ei todennäköisesti olisi saatu esille järvellisiltä alueilta juuri lainkaan. Lisäksi järvien vaikutusta on mahdollista arvioida laskennallisin keinoin. Näistä syistä on ilmeistä, että pienet järvettömät alueet ovat hyödyllisempi työväline kuin pienet järvelliset alueet.

Tämän tutkimuksen perusteella pienet valuma-alueet ovat tarkoituksenmukainen ja osittain korvaamatonkin työväline hydrologisessa tutkimuksessa erityisesti käytännön tarpeiden kannalta arvioituna, mutta myös tieteellisessä mielessä. Ne tarjoavat samalla erinomaisen kehyksen monitieteellisille tutkimuksille. Tällaista hyväksikäyttöä tulisikin tulevaisuudessa entisestään lisätä, kuten mm. kansainvälisissä asiantuntijakokouksissa Helsingissä 1980 ja Bernissä 1982 on korostettu ja johon myös Pohjoismaiden ministerineuvoston työryhmän mietinnössä on viitattu.

LIST OF SYMBOLS

MHq_w	= mean value of spring maximum runoff	$l\ s^{-1}\ km^{-2}$
MHq_s	= mean value of summer maximum runoff	$l\ s^{-1}\ km^{-2}$
$MHq_{w\ inst}$	= mean value of instantaneous spring maximum runoff	$l\ s^{-1}\ km^{-2}$
$MHq_{s\ inst}$	= mean value of instantaneous summer maximum runoff	$l\ s^{-1}\ km^{-2}$
Hq_w 1/20	= spring maximum runoff with return period of 20 years	$l\ s^{-1}\ km^{-2}$
Hq_s1/20	= summer maximum runoff with return period of 20 years	$l\ s^{-1}\ km^{-2}$
$Hq_{w\ inst}$1/20	= instantaneous spring maximum runoff with return period of 20 years	$l\ s^{-1}\ km^{-2}$
$Hq_{s\ inst}$1/20	= instantaneous summer maximum runoff with return period of 20 years	$l\ s^{-1}\ km^{-2}$
Nq	= minimum runoff	$l\ s^{-1}\ km^{-2}$
$MNq_{s\ 30}$	= mean 30-day summer minimum runoff	$l\ s^{-1}\ km^{-2}$
A	= drainage area	km^2
C	= cultivated land	% of area
C_s	= sub-drained cultivated land	% of area
F	= forest	% of area
B	= swampland	% of area
B_o	= open bog	% of area
B_d	= forestry drainage	% of area
b_i	= index of forestry drainage $= \sum \frac{d_i}{t_i}$	
d_i	= percentages of different drainages	% of area
t_i	= time in years from each drainage	
I_s	= paved surfaces and open bedrock	% of area
D_d	= drainage density of main ditches	km^{-1}
F_s	= volume of growing stock in total drainage area	$m^3\ ha^{-1}$
F_c	= coverage of tree stand	% of area
G_r	= percentage coarse soils (gravel, coarse	

	to fine sands, coarse silt and respective moraines)	% of area
G_f	= percentage fine soils (clay, fine and medium silts and respective moraines)	% of area
G_c	= percentage clay soils	% of area
G_g	= percentage gravel soils	% of area
L_b	= length of basin along main channel	km
k_e	= elongation ratio = $A / (L_b)^2$	
k_c	= circularity of basin = A / A_p	
A_p	= area of a circle with equal perimeter	km^2
L_c	= length of main channel	km
S_c	= mean slope of main channel	%
L_w	= distance from outlet to the centre of gravity	km
S_w	= slope from centre of gravity to outlet	%
E_w	= altitude of centre of gravity	m a.s.l.
E_o	= altitude of outlet	m a.s.l.
E_p	= maximum altitude of basin	m a.s.l.
E_d	= maximum difference in altitude	m
S_m	= mean slope of basin	%
s_i	= slope index = relief ratio = ratio between mean altitude of the water divide referred to outlet and divided by basin length	$m\ km^{-1}$
t_w	= time of flow from the centre of gravity to the outlet	h
T_a	= mean annual air temperature	°C
P_a	= mean annual precipitation (corrected)	mm
P_s	= average precipitation of June to August	mm
W_m	= water equivalent of snow on 15 March as long-term average	mm
W_h	= water equivalent of snow on average during study period on 15 March	mm
W_e	= water equivalent of snow on average during study period on 31 March	mm
W_p	= maximum water equivalent of snow on average during study period	mm
c_v	= $\bar{x}/s$ = coefficient of variation	
s	= standard deviation	
s_e	= standard error of estimate	
S_s	= concentration of suspended solids	$mg\ l^{-1}$
a	= coefficient in the equations for suspended solids	
b	= exponent in the equations for suspended solids	
S_1	= measure indicating sorptivity in the Philip infiltration equation	
A_1	= constant in the Philip infiltration equation	
f	= infiltration rate	$mm\ h^{-1}$ $mm\ min^{-1}$
f_0	= initial infiltration	”
f_c	= infiltration capacity	”
k	= constant in the Horton infiltration equation	
K, B, A	= coefficients in a logarithmic infiltration equation	
API_n	= antecedent precipitation index of the n th day	mm
API_{n-1}	= the index of preceding day (n—1)	mm
P_{n-1}	= precipitation of (n—1)th day	mm
k	= coefficient of the month	
d_{10}	= grain size, ten per cent finer by weight	mm
d_{60}	= grain size, 60 per cent finer by weight	mm

d_{90}	= grain size, 90 per cent finer by weight	mm
d_{60}/d_{10}	= coefficient of uniformity or gradedness	
O_t	= thickness of organic matter on soil surface	cm
F_d	= frost depth	cm
R_s	= runoff from subdrains	$l\ s^{-1}\ km^{-2}$

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